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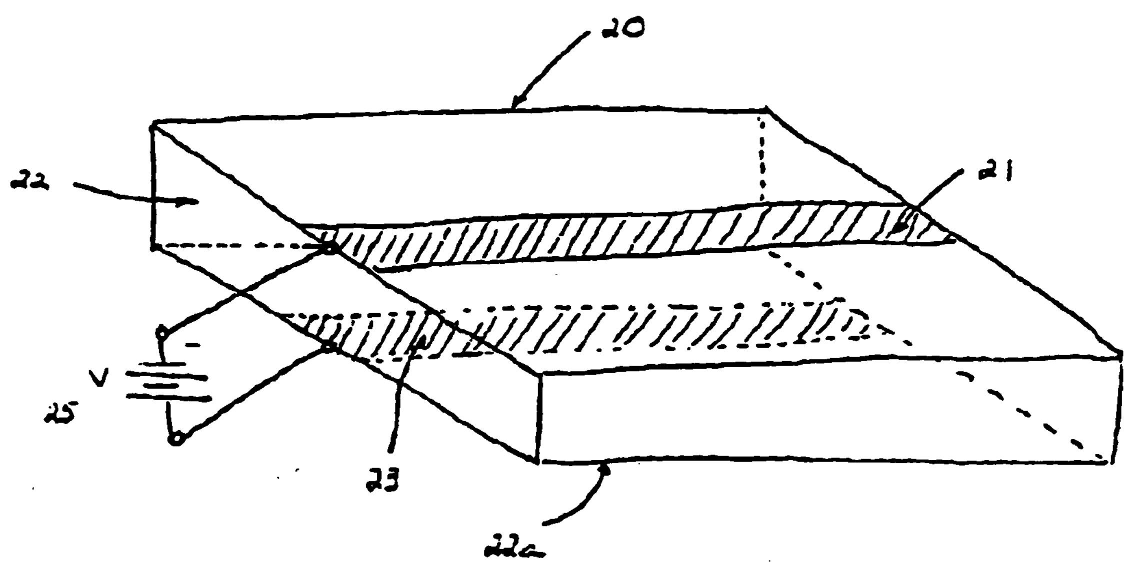


(57) Abstract

The disclosure relates to ferroelectric and superconducting thin films used in combination to produce low-loss frequency tunable microwave and mm-wave devices. Various metal oxide superconducting and ferroelectric films can be arranged in numerous multilayered geometries (figs. 14-19) which can effect microwave and mm-wave signals through the application of a voltage (V) across the ferroelectric film. A preferred embodiment of the invention (figs 1, 2) is the use of the inventive device as a phase shifter or delay line (20) utilizing voltage tunable capacitor structures (21, 23) fabricated from ferroelectric thin films (22) which are responsive to a voltage bias (25). Additional microwave and mm-wave embodiments include resonators (figs 10, 11), filters, coplanar waveguides, phase array antennas (fig. 6), radiative gratings (fig. 7), electrically small antennas (fig. 8), half loop antennas (figs. 23, 24), fringe effect capacitors (figs. 12, 13, 21, 30, 31), artificial transmission lines (fig. 29), etc.

TUNABLE MICROWAVE DEVICES INCORPORATING HIGH TEMPERATURE SUPERCONDUCTING AND FERROELECTRIC FILMS

BACKGROUND OF THE INVENTION

1. Field of the Invention

Ferroelectric films such as $SrTiO_3$, $Pb(Sr,Ti)O_3$, $Sr_xBa_{1-x}TiO_3$, etc. provide a means for producing tuneable capacitors since the dielectric constant of the ferroelectric films is tuneable by variation of voltage applied to the ferroelectric films. Because of their intrinsically low losses at high frequencies, these materials can be implemented in a variety of microwave components, including delay lines and phase shifters.

One of the principle applications of delay lines and phase shifters is for phased array antennas. The voltage-controlled ferroelectric film modulates the dielectric constant and hence the time delay of either microstrip or coplanar delay lines. Such phase shifters or tuneable delay lines can be used to phase delay microwave and millimeter wave signals either transmitted or received from the individual radiative elements of the antenna array.

Such tuneable ferroelectric films can be used in a large family of tuneable microwave components and devices such as phase shifters, matching networks, oscillators, filters, resonators, loop antennas, superconducting film elements, etc.

The invention in general relates to devices which are tuned utilizing the fact that the dielectric constant of a material varies with voltage or some other parameter, and more particularly to such devices that utilize barium strontium titanate as the tuneable dielectric constant material.

2. Description of the Prior Art

Ferroelectric phase shifters are disclosed in "Ceramic Phase Shifters for Electronically Steerable Antenna Systems", Váradan, V.K., et al., Microwave Journal, January 1992, pp. 116-126.

The use of superconductors for microwave frequency transmission is disclosed in "High-Temperature Superconductivity for EW" Ryan, P.A., Journal of Electronic Defense, August 1992, pp. 48-54.

The dielectric properties of thin films of $SrTiO_3$ used as dielectric layers in superconducting field effect (FET) like devices is disclosed in "Dielectric properties of $SrTiO_3$ thin films used in high T_c superconducting field-effect devices", Walkenhourst, A., et al. Appl. Phys. Lett. 60(14), 6 April 1992, pp. 1744-1746.

A superconductor phase shifter using SQUIDS is disclosed in "Monolithic HTS Microwave Phase Shifter and Other Devices", Jackson, C.M., et al. Journal of Superconductivity, Vol. 5 No. 4, 1992, pp. 419-424.

The use of superconductive feed networks and antenna elements of antenna arrays is disclosed in "A Survey of Possible Passive Antenna Applications of High-Temperature Superconductors", Dinger, R.J., et al. IEEE Transactions on Microwave Theory and Techniques, Vol. 39, No. 9, September, 1991.

A thin superconducting film antenna is disclosed in "Radiation Efficiency Measurements of a Thin-Film Y-Ba-Cu-O Superconducting Half-Loop

Antenna at 500 MHZ", Dinger, R.J., et al. Paper Presented at MTT-S, Boston, June, 1991, pp. 1-4.

The dielectric properties of BST material thin films are disclosed in "Microstructure-Induced Schottky Barrier Effects", in Barium Strontium Titanate (BST) Thin Films for 16 and 64 MBIT Dram Cells, Scott, J.F., et al., circa 1992.

It is known that dielectric films in which the dielectric constant of the film is tuneable by varying the voltage applied to the film provide a means for producing tuneable capacitors which can be used in a variety of microwave components, including delay lines, phase shifters, and phased array antennas. In delay lines a voltage applied to the dielectric material modulates the dielectric constant and hence the time of transit, or delay, of an electrical signal passing through the material. Delay lines are commonly fabricated as microstrip or coplanar devices. If the time delay is used to shift the phase of a signal, then the device is called a phase shifter. Such phase shifters or tuneable delay lines can be used to phase delay microwave and millimeter wave signals either transmitted or received from individual radiative elements of an antenna array to create a phased array antenna. Because of their intrinsically low losses at high frequencies, ferroelectric materials, which generally are also materials in which the dielectric constant is tuneable, are particularly useful in such devices. Such tuneable ferroelectric films can be used in a large family of tuneable microwave components and devices including the delay lines, phase shifters, and phased antenna arrays mentioned above as well as matching networks, oscillators, filters, resonators, loop antennas, and many other devices.

Ferroelectric phase shifters, and in particular barium strontium titanate (BST) phase shifters which utilize the change in dielectric constant with a biasing field to generate the phase shift, are disclosed in "Ceramic Phase Shifters for Electronically Steerable Antenna Systems", Varadan, V.K., et al., *Microwave Journal*, January 1992, pp. 116-126. However, the dielectric constant changes and phase shifts are

so small that only bulk devices are feasible.

A high temperature superconductor/ferroelectric phase shifter utilizing the change of the dielectric constant with electric field to vary the phase shift is disclosed in "A High Temperature Superconductor Phase Shifter", Jackson, C.M., et al. *Microwave Journal*, Vol. 5 No. 4, December 1992, pp. 72-78. In particular $Sr_xBa_{1-x}TiO_3$ is mentioned as a responsive material for such phase shifters. Such use of $SrBaTiO_3$ in a voltage controlled dielectric constant tuneable phase shift device is also mentioned in "Novel Monolithic Phase Shifter Combining Ferroelectrics and High Temperature Superconductors", Jackson, Charles M., et al., *Microwave and Optical Technology Letters*. However in both articles, only modest phase shifts of about 10% are disclosed for bulk devices. If these devices were scaled down to microwave integrated circuit (MIC) size, which devices must be made with thin films, the surface effects of the thin films would predominate and the tuneability would become too small to be practically useful. Since MIC devices over many advantages including reliability and low cost, it would be highly desirable to have a dielectric material that provides useful tuneability in such devices.

The dielectric properties of barium strontium titanate (BST) material thin films are disclosed in "Microstructure-Induced Schottky Barrier Effects", in Barium Strontium Titanate (BST) Thin Films for 16 and 64 MBit Dram Cells, Scott, J.F., et al., circa 1992.

The prior art tuneable microwave and millimeter wave devices have all involved compromises between the degree of change of the dielectric constant, lossiness, and other parameters. The dielectric material should have a high degree of change in the dielectric constant to permit maximum tuneability of the device. The lossiness should be low since otherwise the power use of the devices is excessive. Thus it would be a significant advance to have tuneable microwave and millimeter wave devices that have both a large degree of tuneability and low lossiness.

SUMMARY OF THE INVENTION

The present invention relates to the use of ferroelectric insulating thin films as dielectric layers in superconducting thin film structures for fabrication of microwave and millimeter wave devices which are frequency-tuneable. More particularly, metal oxide ferroelectric and superconducting thin films are used in combination to produce an entire new class of microwave and millimeter wave devices which can be frequency-tuned by the application of voltage bias signals across various portions of the ferroelectric thin films. In such structures, because of the low loss performance of superconductors at high frequency, the microwave and millimeter wave performance of the devices are limited mostly by the loss tangent of the ferroelectric dielectric layers. The fundamental materials compatability of a whole class of metal oxide superconductors with a whole class of metal oxide ferroelectric materials provides a thin film material system with unique flexibility for designing and fabricating a multiplicity of multilayer geometries, including ferroelectric on superconductor structures and superconductor on ferroelectric structures.

The invention is especially useful for producing microwave and millimeter wave devices which have the extreme low loss performance of other superconducting devices, but also have the necessary frequency tuneability required for most practical applications. By this invention, it is possible to realize numerous microwave and millimeter wave devices, including, but not limited to, delay lines, phase shifters, resonators, oscillators, filters, electrically-small antennas, half-loop antennas, directional couplers, patch antennas, and various radiative gratings, which are frequency-tuneable by utilizing voltage-tuneable capacitor structures fabricated from voltage-biased ferroelectric thin films in combination with superconducting thin films.

The invention relates to the utilization of both thin films of high temperature superconductor (HTSC) material and thin films of ferroelectric materials for achieving tuneability in a variety of microwave structures.

Ferroelectric films such a $SrTiO_3$, $Pb(Sr,Ti)O_3$, $Sr_xBa_{1-x}TiO_3$, etc. provide a means for producing tuneable capacitor structures at microwave frequencies since the dielectric constant of the ferroelectric films is tuneable by variation of voltage applied to the ferroelectric films. In accordance with the invention, a thin film of ferroelectric material is provided with a thin film (or films) of a high temperature superconductor (HTSC) such as Y-Ba-Cu-O (YBCO) or Tl-Ba-Ca-Cu-O (TBCCO) in order to produce low loss microwave and millimeter wave devices which are frequency tuneable by application of voltage to the thin films of ferroelectric material. The thin film structures of HTSC material and ferroelectric material which are deposited on a substrate result in reduced losses, limited only by the loss tangent of the ferroelectric material and the impedance matching structures. The combination of HTSC thin films and ferroelectric thin films can be used in a large family of tuneable microwave components and devices such as phase shifter devices which offer a method for obtaining true-time delay, superconducting phase shifters, tuneable delay lines, resonators, filters, matching networks, oscillators and tuneable antennas.

The combination of a HTSC thin film and ferroelectric thin films offers a novel class of microwave devices with unique properties including a substantial frequency tunability, simple construction, the potential for optimization of temperature operation ranges, the ability to use variably thin dielectrics, low cost, high level of integration with other components such as antennas and the increased power handling of the circuit. The extent of the tunability of the structures depends upon the ferroelectric material, its form and geometry, (e.g., film thickness), the temperature, and the applied fields or voltage.

Compatibility of YBCO, TBCCO and other superconductors and a broad class of ferroelectric materials enables the optimization of ferroelectric materials and superconducting materials and the growth of alternating layers of each by a variety of deposition methods including evaporation, sol gel, sputtering physical vapor deposition, chemical vapor deposition, laser deposition and others. The combination of HTSC thin films and ferroelectric films provides a novel class of tuneable microwave and millimeter wave devices.

One of the principle applications of the invention comprises phase shifters and tuneable delay lines for phased array antennas. The voltage-controlled ferroelectric thin film modulates the dielectric constant and hence the time delay, of either microstrip line or coplanar delay lines. Such phase shifters or tuneable delay lines can be used to phase delay microwave and millimeter wave signals either transmitted or received from the individual radiative elements of the antenna array. Other applications of the class of tuneable microwave and millimeter wave devices include resonators, filters, matching networks, oscillators, directional couplers and tuneable antennas.

The invention also includes the utilization of a dielectric grating for an individual radiative element in a phased antenna array. Such a grating (with fixed delay between each adjacent element) radiates (or receives) energy at a fixed angle. The angle can be adjusted by biasing the dielectric grating with a single bias voltage. Such a voltage-controlled grating enables steering (in one direction) with the application of a single DC-bias line.

The invention of the dielectric grating can be extended to two-dimensional arrays, with steering in both the x- and y- directions. A simple two-dimensional array of such gratings with a fixed spacing between each grating

"patch" antenna provides a similar fixed radiation angle in the second direction. A second, single voltage bias line modulates the dielectric constant and hence the time delay between each grating structure in the array.

The invention also includes several capacitively coupled devices, including a tuneable superconducting resonator with substantial tunability, a superconducting fringe-effect capacitor with substantial tunability, and application of the tuneable devices to a broad range of resonant devices, including tuneable loop antennas.

The present invention solves the above problem by providing tuneable microwave and millimeter wave devices that utilize barium strontium titanate (BST) as the tuneable dielectric constant material. Preferably the (BST) has the formula $Ba_xSr_{1-x}TiO_3$. Preferably, $0.01 \leq x < 0.2$. As is known in the art, the BST formula can also be written $Sr_yBa_{1-y}TiO_3$.

It has been discovered that BST, especially BST in which the amount of barium is small as compared to the amount of strontium, has extremely high tuneability in microwave and millimeter wave devices. It has been found that the dielectric constant of BST with small amounts of barium as compared to strontium varies typically about 300% and, in some cases, as much as 600% with changes in voltage from zero volts to 25 volts (25 kilovolts/cm), which voltage range is well within the operating voltage range of typical tuneable microwave and millimeter wave devices. Such high variability of the dielectric constant permits tuneable devices to be fabricated in which the dielectric portions of the circuits are extremely thin, thereby minimizing loss. Since loss in the dielectric portion is minimized, the conductor portion may utilize conventional conductors and still have loss factors that are of the order of the loss factors of devices fabricated with superconductors and conventional dielectric materials.

Preferably the BST microwave and millimeter wave devices are designed to operate at temperatures of between 50 K and 110 K. The BST has been found to have maximum tuneability in this temperature range.

It further has been found that by varying the relative amounts of barium and strontium within the range $0.01 \leq x < 0.2$, the tuneability of the devices can be varied over a wide range. Generally, as the amount of strontium is increased, the peak tuneability shifts to higher temperatures. Thus by varying the relative amounts of barium and strontium in the dielectric portion of the devices, devices with different responses over the same voltage range may be constructed.

In another aspect, the invention provides a tuneable electrical device comprising: a dielectric material; means for maintaining the dielectric material at a temperature between 67 K and 110 K; signal input means for inputting an electrical signal to the dielectric material; and electrical bias means for applying an electrical field to the dielectric material to determine the dielectric constant of the material and tune the electrical signal.

In a further aspect, the invention provides a tuneable electrical device comprising: a thin film of a dielectric material having a dielectric constant that varies with the electric field applied to the material; signal input means for inputting an electrical signal to the dielectric material; and electrical bias means for applying an electrical field to the dielectric material to determine the dielectric constant of the material and tune the electrical signal.

The invention thus, for the first time, provides a tuneable electrical device in which thin film devices have sufficient tuneability for practical applications. Numerous other features, objects and advantages of the invention will become apparent from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a specific embodiment of the invention, a tuneable delay line, showing a microstrip line of HTSC material deposited on a thin film (substrate) of ferroelectric material, all deposited on a crystalline substrate;

FIG. 2 is a schematic representation of the tuneable superconductor/ferroelectric thin film device of the invention;

FIG. 3 is a plot of the Magnetic Flux Screening - Temperature characteristic for a multilayer superconductor/ferroelectric thin film structure of the invention after deposition as measured by a mutual inductance technique;

FIG. 4 is a plot of Insertion Loss vs. Frequency at 77 K for the tuneable resonator of the invention;

FIG. 5 is a fragmentary vertical section view of a thin film of HTSC material contiguous with the opposite surface of a film of ferroelectric material;

FIG. 6 is a schematic representation of the phase shifter of the invention in a phased array antenna system;

FIG. 7 is a fragmentary vertical section view of a dielectric grating in accordance with the invention for an individual radiative element in an antenna array;

FIG. 8 is a schematic representation of a two-dimensional array of dielectric gratings in accordance with the invention for an antenna array;

FIG. 9 is a perspective view of a coplanar structure of the invention formed on a $LaAlO_3$ substrate;

FIG. 10 is a perspective view of a resonant cavity formed by coplanar cavities in accordance with the invention;

FIG. 11 is a schematic representation of a capacitively coupled microstrip line resonator with a tuneable ferroelectric capacitor and a capacitively

coupled microstrip line resonator without tunability;

FIG. 12 is a plan view of a superconducting fringe effect capacitor in accordance with the invention; and

FIG. 13 is an elevation view of the capacitor of FIG. 12.

FIG. 14 is a cross sectional view of a specific multilayer structure of the invention, with a HTSC layer on top of a ferroelectric layer.

FIG. 15 is a cross sectional view of a more general multilayer structure of the invention, with a HTSC layer on top of a ferroelectric layer on top of a substrate.

FIG. 16 is a cross sectional view of a specific structure of the invention, in which a HTSC layer is deposited directly on a ferroelectric substrate.

FIG. 17 is a cross sectional view of a specific multilayer structure of the invention, with a ferroelectric layer deposited on top of a patterned HTSC layer (deposited on a substrate) with the ferroelectric layer also filling in the etched regions of the HTSC layer.

FIG. 18 is a cross section view of a specific structure of the invention in which a ferroelectric layer and HTSC layer lie in the same plane, with the HTSC-ferroelectric interface of the invention being at the edges of the films.

FIG. 19 is a cross sectional view of a general multilayer structure of the invention with various combinations of HTSC and ferroelectric layers on a bulk crystalline dielectric, insulating, or ferroelectric substrate.

FIG. 20 is a fragmentary vertical section view of coplanar thin films of HTSC material contiguous with one surface of a thin film of ferroelectric material and a thin film of HTSC material contiguous with the other surface of the thin film of ferroelectric material.

FIG. 21 is a plan view of an interdigitated capacitor of the invention;

FIG. 22 is a fragmentary vertical section view of the interdigitated capacitor of FIG. 21;

FIG. 23 is a plan view of a half-loop antenna of the invention;

FIG. 24 is a schematic representation of the resonant circuit of the antenna of FIG. 21.

FIG. 25 is a cross sectional view of a BST delay/shift element according to the invention showing the application of a bias filed to the element;

FIG. 26 is a block diagram of a microwave/millimeter wave delay/shift device utilitzing the delay/shift element of FIG 25;

FIG. 27 is a cross-sectional illustration of a microwave/millimeter wave delay/shift device utilizing a delay/shift element according to the invention;

FIG. 28 is a perspective view of a portion of a microstrip transmission line embodiment of a delay/shift element according to the invention;

FIG. 29 is a schematic diagram of an artificial trasmission line utilizing a lumped capacitance delay/shift element according to the invention;

FIG. 30 is an illustration of a capacitor device used in obtaining bulk capacitance change data for BST samples;

FIG. 31 is an illustration of a capacitor device used in obtaining thin film capacitance change data for BST samples;

FIG. 32 is an illustration of a coplanar waveguide phase shifter element according to the invention;

FIG. 33 is a cross-sectional view of the phase shifter of FIG. 32 taken through the line 9-9 in FIG. 8;

FIG. 34 shows capacitance versus temperature curves for five electric field strenghts for a Ba0.09 Sr0.91 TiO3 capacitor as shown in FIG. 30;.

FIG. 35 shows capacitance versus temperature curves for five electric field strengths for a Ba0.09 Sr0.91 TiO3 capacitor as shown in Fig. 30;

FIG. 36 shows capacitance versus temperature curves for six electric filed strengths for a Ba0.08 Sr0.92 Ti03 thin film capacitor as shown in FIG. 31;

FIG. 37 shows capacitance versus temperature curves for four electric field strengths for a Ba0.08 Sr0.92 Ti03 thin capacitor as shown in FIG. 31, which capacitor is smaller than the capacitor used in obtaining the curves of FIG. 36, and also shows a single point on the capacitance/temperature curve for three other electric field strengths;

FIG. 38 shows loss tangent versus temperature curves for the same capacitor and electric field strengths used in obtaining the curves of FIG. 36;and

FIG. 39 shows the measured change of phase angle and effective dielectric constant versus electric field strength for the phase shifter of FIGS. 32 and 33.

DESCRIPTION OF PREFERRED EMBODIMENTS

Discoveries of high temperature superconducting (HTSC) materials such as the 30-K La-Ba-Cu-O superconductor and the 90-K Y-Ba-Cu-O superconductor have stimulated a worldwide race for higher temperature superconductors. Breakthroughs have been made by the discoveries of the 90-K Tl-Ba-Cu-O system, the 110-K Bi-Ca-Sr-Cu-O system, and the 120-K Tl-Ba-Ca-Cu-O (TBCCO) system. The Y-Ba-Cu-O system is the first rare earth system which reaches zero resistance above the liquid nitrogen boiling point while the Tl-Ba-Ca-

Cu-O system reaches zero resistance above 100K and has the highest zero-resistance temperature (127K).

A number of superconducting phases, including $Tl_2Ba_2Ca_2Cu_3O_{10+x}$ (2223) and $Tl_2Ba_2Ca_1Cu_2O_{8+x}$ (2212) have been isolated from the Tl-Ba-Ca-Cu-O system. The 2223 superconductor has a 3.85 x 3.85 x 36.25 Å tetragonal unit cell. The 2122 superconductor has a 3.85 x 3.85 x 29.55 Å tetragonal unit cell. The 2223 phase is related to 2122 by addition of extra calcium and copper layers. In addition, the superconducting phase in the Ca-free Tl-Ba-Cu-O system is $Tl_2Ba_2CuO_{6+x}$ (2201).

The new class of tuneable microwave devices of the invention combines the low loss of a high temperature superconductive (HTSC) material (such as Tl-Ba-Ca-Cu-O and Y-Ba-Cu-O) in a thin film with the variable dielectric properties of a thin film of ferroelectric material.

Ferroelectric thin films such a $SrTiO_3$, $Pb(Sr,Ti)O_3$, Sr_xBa_{1-x} TiO_3, etc. provide a means for producing low-loss tuneable capacitor structures at microwave and millimeter wave frequencies since the dielectric constant of the ferroelectric thin films is tuneable by variation of voltage applied to the films. A thin film of ferroelectric material is provided with a thin film of a high temperature superconductor (HTSC) material such as Y-Ba-Cu-O or Tl-Ba-Ca-Cu-O. The HTSC thin film results in a multilayer structure with reduced losses, limited only by the loss tangent of the ferroelectric material and the impedance matching structures. The combination of HTSC thin films and ferroelectric films can be used in a large family of tuneable microwave components and devices such as phase shifter devices which offer a method for obtaining true-time delays in

tuneable delay lines, tuneable filters, matching networks, oscillators, loop antennas, directional couplers, resonators, etc.

The thin film of ferroelectric material, e.g., $SrTiO_3$ and various barium doped strontium titanate materials provide an excellent substrate for the deposition of an HTSC material such as $YBa_2Cu_3O_{7-\delta}$ (YBCO) or Tl-Ba-Ca-Cu-O (TBCCO). $SrTiO_3$, and its relatives, have a perovskite crystal structure with an excellent lattice match and thermal expansion coefficient close to that of YBCO, Tl-Ba-Ca-Cu-O, and other thallium copper oxide superconductors. In general other substrates can also be used, such as lanthanum aluminate, etc.

The combination of HTSC thin films and ferroelectric thin films offers a novel class of tuneable microwave and millimeter wave devices with unique properties including a substantial frequency tuneability, simple construction, the potential for optimization of temperature operation ranges, the ability to use variably thin dielectrics, low cost, high level of integration with other components such as antennas, and the power handling of the circuit. The extent of the tuneability of the structures depends on the materials, their forms and geometrics (e.g. film thickness), the temperature, and the applied voltage.

High quality $SrTiO_3$, $BaSrTiO_3$, $LaA1O_3$ and other dielectric thin films can be deposited on HTSC thin films (e.g., YBCO or Tl-Ba-Ca-Cu-O) films by sol-gel, plasma-spray, sputtering, physical vapor deposition, chemical vapor deposition, laser deposition, and other techniques. Superconducting properties of the HTSC layer depend on the compatability with the ferroelectric thin film and vice-versa, as well as on processing conditions. In practical circuits, a fixed temperature of operation is required to provide good impedance matching. Broadband, compact,

low loss, thin-film, superconducting matching circuits are available. A thin film multilayer implementation of the class of tuneable superconducting/ferroelectric structures of the invention has the added benefit that monolithic devices and integrated circuits can be designed.

As shown in FIG. 1, a tuneable delay line 20 is formed by a patterned microstrip line 21 of a thin film of HTSC material, for example YBCO material, deposited on a thin film 22 of ferroelectric material which is deposited on ground plane 23. In turn ground plane 23 is deposited on a crystalline substrate such as $SrTiO_3$. The ferroelectric thin film 22 can be, for example, from 100 Å to 10000 Å thickness. By applying a voltage between the superconductor or microstrip line 21 and a ground plane 23, a DC bias is provided to the ferroelectric layer, thereby changing the dielectric constant and the wave propagation velocity within the layer. Note that both the microstrip line and the ground plane can be made from HTSC material.

The microstrip line or pattern 21 of a YBCO thin film is deposited on the $SrTiO_3$ thin film substrate 23 by using sol-gel, chemical vapor deposition, physical vapor deposition, sputtering, laser deposition, or other techniques. Sol-gel deposition and chemical vapor deposition of superconducting thin films and ferroelectric thin films is disclosed in U.S. Patent Nos. 5,119,760 and 5,138,520, assigned to Symetrix Corporation of Colorado Springs, Colorado.

FIG. 2 shows a schematic representation of the tuneable delay line 20 including the microstrip line or thin film of the (HTSC) YBCO material 21. A normal metal (e.g. silver) or HTSC material ground plane 23 is deposited on the rear surface 22a of substrate or film 22. Variable voltage source 25 enables a variable

voltage to be applied as an electric field to the ferroelectric layer 22 by means of microstrip line 21 and ground plane 23.

$SrTiO_3$ belongs to the $BaTiO_3$ group in the classification of ferroelectric materials. $BaTiO_3$ is a well known ferroelectric material and its phase transition from cubic to tetragonal, where a small displacement of Ti in the tetragonal phase under the external electric field, is responsible for ferroelectricity. $SrTiO_3$ has three crystalline phase transitions at lower temperatures (see Table 1).

Table 1
LOW TEMPERATURE PHASE TRANSITION OF $SrTiO_3$

TEMPERATURE(K)	STABLE PHASE	PHYSICAL CONSTANT
>110	cubic	a = 3.902A
65-110	tetragonal	c/a = 1.00056
35-65	orthorhombic	a:b:c = 0.9998 : 1 : 1.0002
<10	Possibly rhombohedral	

Other ferroelectric materials which can be used for thin film 22 include $BaTiO_3$, $LiNbO_3$, $Pb(Sr,Ti)O_3$, $Sr_xBa_{1-x}TiO_3$. etc. Other materials from the III-V, and II-VI groups could be used with other buffer layers to solve any lattice matching problems which arise should epitaxial deposition be required.

The extent of tuneability of the tuneable delay line 20 depends upon the ferroelectric material, the temperature, and the applied field or voltage.

An advantage of the superconductor/ferroelectric tuneable delay line 20 of the invention is its power handling capability. Distortion can arise in a non-

linear transmission line when the RF voltages become comparable to the DC control voltages. The power handling of a microstrip line can be estimated from the minimum bias voltage to be used. Power is given by $P=V^2/Z$. Accordingly, for a 5 volt bias and a 1 ohm impedance, 25 watts (i.e. >40 dBm) could be handled before the non-linearities become apparent. The level of high power will set the microstrip line width requirement to insure that the critical current carrying capacity of the line is not exceeded.

FIG. 3 shows changes in resistance with changes of temperature of the multilayer superconductor/ferroelectric thin film structure of the invention after deposition.

FIG. 4 shows the change in insertion loss plotted against frequency at 77K for the tuneable resonator of the invention.

FIG. 5 shows a microstrip line 31 of HTSC material in section. As shown in FIG. 5, the thin film of the HTSC material 32 of microstrip line 31 is deposited upon thin film 34 of the ferroelectric material. Thin film 34 of ferroelectric material is contiguous with thin film 33 of HTSC material. Crystalline substrate 35 supports thin films 33, 34 and 32.

Where size, weight, and drive mechanisms are limited, the traditional moving reflector antenna is being replaced in some applications by phased array antennas. Generally planar in shape, conventional phased array antennas are formed by a substantial number of closely spaced, individual radiators, whose composite beam can be shaped and spacially directed in microseconds, thereby enabling the antenna to track a multitude of targets at one time. This is accomplished electronically by RF phase shifters associated with each individual

radiating element. No moving parts are required.

State of the art passive phased array antennas are limited in their application by cost, more than any other factor. The required phase shifters are not cheap and with a typical array requiring thousands of individual antenna elements, each with its own phase shifter, the price of the total system becomes prohibitive.

The principal difficulty of such phased arrays is that for large arrays, i.e. antenna arrays with a large number of radiative elements, the need to control each individual time delay to each radiative element requires that each individual phase shifter be independently voltage-biased. Arrays as large as 100x100 radiative elements necessarily require 10,000 independently-controlled bias voltage lines, which can be prohibitive in complexity and cost.

The ferroelectric phase shifter design is based upon a material whose dielectric permittivity can be made to vary by application of a DC electric field, parallel to the polarization of the RF energy, and normal to its direction of propagation. Variations in permittivity alter the RF propagation velocity, and if connected to a waveguide structure, will change the cutoff wavelength and dispersion of the waveguide itself. These two effects translate into propagation phase variation. A short waveguide section containing a phase shifter of ferroelectric material and HTSC material constitutes the key element for accomplishing electronic scanning in a phased array antenna configuration.

A typical application of the thin film HTSC material and ferroelectric thin film technology of the invention is for phase shifters for phased array antennas. The voltage-controlled ferroelectric thin film can be used to modulate

the dielectric constant, and hence the time delay, of either microstrip line or coplanar delay lines. Such phase shifters or tuneable delay lines can be used to phase delay microwave and millimeter wavelength signals either transmitted or received from the individual radiative elements of the antenna array.

As shown in FIG. 6, the phased array antenna 40 of the invention includes a plurality of radiators 41. The antenna input 42 from a source of a electromagnetic radiation such as that at a microwave frequency is provided with a power distribution network 43. The distribution network connects the antenna input to each of a plurality of phase shifters 44 in accordance with the invention. The thin superconducting film of each of phase shifters 44 is connected by leads 45 to control circuit 46. The control circuit is driven by programmer 47 to control the voltage applied by the thin superconductor film to the ferroelectric film of each of the phase shifters 44. Thus, the dielectric permittivity of the ferroelectric thin film of each of phase shifters 44 can be varied by the application thereto of a variable DC electric field. The DC electric field is applied normal to the direction of propagation of the RF energy and parallel to the polarization of the RF energy being transmitted through the phase shifter to the radiators 41 of phased array antenna 40. Variations in permittivity of the ferroelectric thin film material alter the RF propagation velocity and can change the cutoff wavelength and dispersion of the RF energy being delivered to the radiators 41 of the antenna. As a result there is a variation in the propagation phase of one radiator with respect to another. Thus programmer 47 by means of control circuit 46 can effect electronic scanning of the phase shifters 44 connected to the radiators 41 of antenna 40 and thereby enable the beam produced by antenna 40 to be shaped into a predetermined form

and to be directed in microseconds. In this way the RF energy radiated by the antenna can track a multitude of targets at one time.

Another embodiment of the invention as shown in FIG. 7 comprises a dielectric grating 50 for an individual radiative element in an antenna array. The grating comprises a base portion 50a and a plurality of elements 50b projecting from base portion 50a and spaced apart from one another. Grating 50 which is formed, for example, of a thin film of ferroelectric material with a fixed time delay determined by the spacing between each adjacent element 50b intrinsically radiates (or receives) RF energy at a fixed angle θ. The angle θ is adjusted by biasing the dielectric grating 50 with a bias voltage from variable bias voltage source 51. Such a voltage-controlled grating enables changing or steering (in one plane) of the radiation angle θ with the application of a variable bias voltage from the source 51 to the grating 50 by lead 52.

In FIG. 8 there is shown a two-dimensional array antenna with steering of the radiation angle θ in both the x and y planes. A two-dimensional array 53 of gratings 54 is shown in FIG. 8. A fixed spacing between each grating "patch" antenna element 55 formed by a grating 50 as shown in FIG. 7 provides a similar radiation angle in the second plane. Voltage bias lines 56 and 57 connected to arrays 58 and 59, respectively, modulate the dielectric constant of the gratings and thereby the time delay between each antenna element 55 in the arrays 50 and 59 which make up antenna 53.

The thin film superconductor/ferroelectric technology of the invention can also be used with:

(1) Tuneable cavities and resonators;

(2) Tuneable frequency and wavelength filters;

(3) Ferrite thin film isolators;

(4) Directional coupler switches;

(5) Phase shift feeder networks for patch antennas;

(6) Coplanar lines with variable impedance using voltage-tuned meander lines as the center conductor of the coplanar line;

(7) tuneable resonant antennas;

(8) tuneable electrically small antennas; and

(9) Tuneable, one-dimensional confocal resonators which can provide higher Q.

A coplanar structure 60 in accordance with the invention is shown in FIG. 9. Structure 60 includes ferroelectric film 61 overlying $LaAlO_3$ substrate 62. Thin films 63 of HTSC (e.g., YBCO or TBCCO) material are deposited on film 61 of ferroelectric dielectric material such as barium strontum titanate (BST) material, the lower surface of which is contiguous with the upper surface of the substrate of a $LaAlO_3$ (LAO) material.

FIG. 10 shows a structure 15 having a center section 66 of YBCO material forming a half wave-length resonator with coplanar lines 66 and 67 which are disposed between coplanar lines 68 and 69. The lines 66-69 are deposited on a dielectric film 70 of BST material. Changes in the thickness of the substrate 71 which, for example, can be $LaAlO_3$ material, modify the effective dielectric constant of film 70 of BST material and the percentage change of this dielectric constant

with the variable voltage applied to dielectric film 71 by voltage source 72.

FIG. 11 shows an capacitively coupled microstrip resonator 80. The dimensions shown on FIG. 11 are by way of example. The resonator includes microstrips 81 and 82 of superconductor (HTSC) material. Strip 83 of thin film ferroelectric material extends over gap 84 between strips 81 and 82. Strips 85 and 86 of HTSC material are connected by leads 87 and 88, respectively, to strips 81 and 82, respectively. If the resonator 80 of FIG. 11, by way of example, is deposited on 17 mils of $LaAlO_3$ (LAO) material with $\epsilon_r = 24.5$, then the effective dielectric constant, ϵ_{eff} is $\epsilon_{eff} \simeq 20$.

Inductively coupled resonator 90 in FIG. 11 having no tunability includes strip 91 of HTSC material connected by leads 92 and 93 to strips 94 and 95 of HTSC material, respectively. If the untuneable resonator 90 is approximated as a section of transmission line comprising two parallel spaced conductors with open ends, then its resonant frequencies is:

$$f_n = \frac{c}{\sqrt{\epsilon_{eff}}} \quad \frac{n}{2}$$ where, for example, = 9mm, n = 1,2,3 ...

This gives f ~ 3.7 GHz, 7.4 GHz, 11.2 GHz, etc.

The ferroelectric series capacitor 84 in the tuneable resonator 80 will affect those resonant modes with large currents in the region of the ferroelectric capacitor. These are the antisymmetric resonant modes, i.e., modes with odd "n" in the above equation. Transmission line analysis yields a transcendental equation for the increased resonant frequencies of these modes:

$$-\frac{1}{\qquad} = \frac{1}{\quad}$$

$$\tan K \frac{}{2} \qquad \frac{2\pi Z_0 C}{2}$$

where

C = capacitance

Z_0 = characteristic impendance = 7

= effective length of the resonator

(open end to open end length)

$$k = \frac{2\pi fc}{\sqrt{\epsilon_{eff}}} \quad \text{for TEM mode,}$$

where

c is the speed of light and

f is the frequency of the resonant mode.

It is estimated that the capacitance is C ~ 1 pF. This gives a resonant frequency spectrum of:

6.7 GHz, 7.4 GHz, 13.43 GHz, . . .

Under a DC bias, the 6.7 Ghz, 13.43 Ghz, ... modes will increase in frequency due to the voltage tuneable dielectric constant change.

In FIGS. 12 and 13 there is shown a superconducting fringe effect capacitor 100 comprising a thin film of ferroelectric material 101 disposed on a substrate 101a. Thin films 102 and 103 of HTSC material are deposited on ferroelectric thin film 101. Pads 104 and 105 are connected by leads 106 and 107, respectively, to thin films 102 and 103, respectively. Variable voltage source 106 is connected by lead 107 and 108 to pads 104 and 105, respectively, and thereby across thin films 102 and 103. The thin film of ferroelectric material 101

has a fringe effect capacitance region 109 disposed between thin films 102 and 103 of HTSC material. By applying a variable voltage across the thin films 102 and 103, the dielectric constant of the ferroëlectric material 101 can be tuned.

As shown in FIG. 14, a HTSC layer A1 is deposited on a ferroelectric layer A2, and the HTSC layer can be subsequently patterned to produce a variety of structures A3. In this geometry, the HTSC/ferroelectric interface A4 is perpendicular to the C-axis of the layers, and lies in the plane of the layers.

As shown in FIG. 15, a HTSC layer A1 is deposited on a ferroelectric layer A2 which is deposited on a substrate A5. Again, the HTSC/ferroelectric interface A4, and the ferroelectric/substrate interface A6 lie in the plane of the layers.

As shown in FIG. 16, a HTSC layer A1 is deposited directly on a ferroelectric substrate A7, with the HTSC/ferroelectric interface A4 being coincident with the HTSC/substrate interface, again lying in the plane of the layers.

As shown in FIG. 17, a ferroelectric layer A2 is deposited on top of a patterned HTSC layer A8 (with example etched feature A9 shown), which is deposited on a substrate A7. The ferroelectric layer A9 fills the etched regions A9 and forms HTSC/ferroelectric interfaces A4 between the overlying ferroelectric layer A2 and HTSC layer A8 and interfaces A10 between the ferroelectric layer A2 and the edges of the patterned HTSC film A8. The interface all between the ferroelectric film A2 and the crystalline (or film) substrate A7 (made of dielectric, insulator, ferroelectric, or other material) is also shown.

As shown in FIG. 18, a ferroelectric layer A12 and HTSC layer are deposited in the same plane, with the HTSC/ferroelectric interface A10 lying at the

edges of the layers. Such layers can be deposited on a variety of substrates A7.

As shown in FIG. 19, a variety of structures A1 - A9 are shown in combination, representing one example of the more general multi-layer structure of the invention, with various patterned and unpatterned HTSC and ferroelectric layers lying on top of each other, in various orders, and with the entire structure lying on a substrate. In the general structure, the substrate could be made of a bulk crystalline sample or film of any number of materials, including dielectrics, insulators, ferroelectrics, etc.

All the layers described can be deposited by a variety of techniques, including physical vapor deposition, chemical vapor deposition, laser deposition, sputtering, sol gel, etc.

In FIG. 20 there is shown a multilayer component 110 of the invention comprising thin films 111 and 112 of HTSC material contiguous with thin film 113 of ferroelectric material. The lower surface of ferroelectric thin film is contiguous with the upper surface of thin film 114 of HTSC material. The lower surface of thin film 114 is contiguous with the upper surface of substrate 115.

FIG. 21 is a plan view of an interdigitated capacitor structure 120 in accordance with the invention. Thin films 121 and 122 of HTSC material have a plurality of projections 121a and 122a, respectively, which nest with respect to one another, thereby forming a meandering slot 123 in structure 120. As shown in FIGS. 21 and 22, a thin film 124 of ferroelectric material overlies the portions of thin films 121 and 122 adjacent meandering slot 123 and extends into the slot itself. The structure 120 enables the overall value of the capacitance of structure

120 to be increased while maintaining tuneability of the capacitance by the application of predetermined voltages to thin film 124.

FIG. 23 shows a tuneable antenna 130 in accordance with the invention. The tuneable antenna comprises half-loop 131 of a thin film of HTSC material. Layers of insulating material 132 and 133 support the half-loop antenna 131. Layers 132 and 133 are separated by thin film 134 of HTSC material. Thin film 135 of HTSC material is connected to half-loop 131. Thin film 136 of ferroelectric material is disposed between thin film 135 and thin film 137 of HTSC material which is disposed on substrate 138. Thin films 135 and 140 with film 133 therebetween form tuneable capacitor 141.

In FIG. 24 there is shown the equivalent circuit of the half-loop antenna 130 of FIG. 21. Driving signal source 142 is connected to the thin film 140 and thereby to the capacitor 141. As shown in FIG. 24, inductance 143 and resistance 144 are the lumped values of the resistance R and the inductance L of the half-loop antenna. The application of a DC voltage across capacitor 141 tunes the capacitance thereof and hence the frequency of the resonance of the circuit comprising the half-loop antenna 131 and the capacitor 141.

Directing attention to FIG. 25, a delay/shift element 216 according to the invention is shown. Delay/shift element 16 comprises a layer 218 of a dielectric material, such as barium strontium titanate (BST), sandwiched between a first conductor 219 and a second conductor 221, which conductors are commonly referred to as electrodes. A DC or low frequency electric field is placed across the BST layer 218 by a variable bias voltage source 223. As can best be seen in FIG. 34, the dielectric constant, and thus the capacitance, of the BST layer 18 changes approximately 500% as the electric field strength goes from 0 kV/cm (kilovolts per centimeter) to 25 kV/cm. This large change in dielectric constant can be used to tune electronic parameters which depend on the dielectric constant. For example, the speed of an electromagnetic wave in a waveguide depends on the dielectric constant of the material that fills the waveguide. Thus tuneable delay lines, phase shifters and other electronic devices that depend on the velocity of an electromagnetic wave in a dielectric medium can be constructed utilizing element 216. In this disclosure such electronic devices shall be referred to as delay/shift devices for simplicity. Also, the terms "waveguide", "transmission line", and "electrical circuit" are conventionally used interchangeably in the field of microwaves and millimeter waves and shall be so used herein. In general the term "transmission line" shall be used to mean either a waveguide, as in the case where the wave length of the signal being processed is of the same order or smaller than the size of the system components, or an electrical circuit, as in the case where the wave length of the signal being processed is much larger than the size of the circuit components.

The generalized structure of a microwave/millimeter wave delay/shift device 224 utilizing the delay/shift element 216 is shown in FIG. 26. It comprises a signal input means 226, the delay/shift element 216 which generally forms part of a transmission line 225 shown by dotted lines, a signal output means 227, and a delay/shift controller. The signal input means 226 typically comprises a terminal for connecting to an electrical signal, or, in terms of waves, a coupling to a wave source, a

transformer, and a polarizer which introduce a wave 228 into transmission line 211. It may also include the signal or wave source, though this is not shown in the drawings. The phrase "signal input means" should be interpreted broadly as anything that inputs an electrical signal to the delay shift element 16, and in particular the dielectric material 218 in the delay/shift element. By "inputting a signal to the dielectric material" is meant that the signal is input so it passes through or otherwise interacts with the dielectric material so that the change in dielectric constant of the material can tune the signal. The delay/shift controller 223 preferably is a variable voltage source 223 as shown in FIG. 25 The wave 228 is delayed or phase shifted by delay/shift element 16 and then is output from the delay/shift device 224 via the signal output means 227, which preferably comprises a polarizer, transformer, and a coupling to further elements of a microwave or millimeter wave system. Again, it may also simple comprise a terminal. The delay/shift device 224 also preferably includes a temperature controller 229. Temperature controller 229 is preferably a cooling device, such as a liquid nitrogen cryogenic device which maintains the temperature of the delay shift element 216 at a predetermined temperature between 50 K and 110 K.

It should be understood that the figures, such as FIG. 25 depicting the delay/shift element 216 and FIGS. 27 and 33 depicting transmission lines or waveguides, are not meant to be actual cross-sectional or other views of any particular portion of an actual electronic device, but are merely idealized representations which are employed to more clearly and fully depict the structure and process of the invention than would otherwise be possible. Likewise it should be understood that the signal input means 226, the signal output means 227, and the delay/shift element 216 may have many other structures than those discussed above and below. For example, in the case of micro circuits which are relatively small compared to the wavelength of the signal being processed, the input means 226 and output means 227 may each simply consist of an electrical terminal.

The delay/shift element 216 may be used with a wide variety of electronic devices including tuneable delay lines, tuneable filters, matching networks, oscillators, loop antennas, directional couplers, tuneable resonators including one-dimensional confocal resonators, tuneable cavities, tuneable frequency and

wavelength filters, ferrite thin film isolators, directional coupler switches, phase shift feeder networks for patch antennas, coplanar lines with variable impedance using voltage-tuned meander lines as the center conductor of the coplanar line, tuneable antennas such as tuneable resonant antennas and tuneable electrically small antennas, phase shifters for phased array antennas, dielectric gratings for an individual radiative elements in an antenna array, fringe effect capacitors and many other structures, all of which may be fabricated in conventional and hybrid circuit form as well as in the form of monolithic devices and integrated circuits.

In this disclosure "thin film" means a film of a thickness of 50 microns and less and preferably 10 microns and less. In this disclosure the term "electrical" is intended to be a broad term that includes the usual meaning of the term electrical as well as everything included under the terms "electromagnetic" and "electronic".

Turning now to a more detailed description of the invention, the delay/shift element 216 (FIG. 1) preferably comprises dielectric layer 218 and electrical bias means 217 for applying an electrical field to the dielectric material 218. Electrical bias means 217 preferably comprises first conductor 219, second conductor 221, and electrical connecting means 217A for connecting the conductors to variable voltage means 223, which typically is an adjustable DC and/or low frequency voltage source. However, the electrical bias means 217A may include only one electrode 219 and one connecting wire 217A; that is, the delay shift element 216 can be made in the form of single electrode 219 and the dielectric layer 218, which element 216, in a later stage of manufacturing the final device to be tuned, is pressed onto a ground plane which acts as the second electrode 221. In the preferred embodiment, the dielectric layer 18 is a ferroelectric material, such as barium strontium titanate (BST), barium titanate ($BaTiO_3$), strontium titanate ($SrTiO_3$), lithium niobate ($LiNbO_3$), lead strontium titanate ($Pb[Sr,Ti]O_3$), lead titanate $(PbTiO)_3$ and others. In the embodiment shown in the figures, the dielectric layer is BST, and is in the form of a thin film 218. Conductors 219 and 221 are preferably formed as thin film layers in contact with the opposing surfaces 220 and 222 of BST layer 218 to form a sandwich structure. However, the conductors may be separated from the BST layer 218 by some

distance, providing they are arranged so that they can apply an electric field to the BST layer 18. In the preferred embodiment the conductors 219 and 221 are made of a superconductor such as Y-Ba-Cu-O (YBCO) or Tl-Ba-Ca-Cu-O (TBCCO), though they also may be conventional conductors, i.e. conductors that are not a superconductor, such as platinum, gold, silver, and tungsten. Generally the conductive layers 219 and 221 are made of several thin layers of different conductors, as for example, an adhesion layer of titanium or chromium immediately adjacent the surfaces 220 and 222 and a layer of platinum or gold in contact with the adhesion layer. Such multilayered structures for electrodes and other conductive elements are well-known in the art and thus will not be discussed in detail herein. Means 217A for connecting conductors 219 and 221 to a voltage source, typically comprises a wiring layer in an integrated circuit, traces in a hybrid circuit, terminals on the element 216 which permit a voltage source to be connected to it, or simply solder points.

In the preferred embodiment, BST layer 218 is barium strontium titanate having the formula $Ba_xSr_{1-x}TiO_3$ where, preferably, $0.01 \leq x < 0.2$. A value of x approximately equal to 0.1 has been found to give the greatest change in dielectric constant. A variable bias voltage source 23 connected across conductors 219 and 221 provides a variable electric field, preferably in the range of zero to 25 kV/cm, across BST layer 218 to vary the dielectric constant. As shown in FIG. 26 when the delay/shift element 216 is placed in a transmission line 225, connected between a signal input means 226 and a signal output means 227, the variable bias voltage source 223 becomes a delay/shift controller 223 which controls the delay, shift, or other parameter that varies with the dielectric constant of the BST layer.

FIG. 27 illustrates a microwave/millimeter wave delay/shift device 230 utilizing a delay/shift element 216A according to the invention in which the wavelength of the signal being processed is of the same order of size or smaller than the electronic components 232, 235A, 236A, 233, etc. The device 230 includes a housing 231, a signal input 32 which couples a signal to the device 230, a transmission line 233, which would generally be called a waveguide in this device, a signal output 234 which couples the signal output from device 230 to an external waveguide (not shown), transformer 235A which transforms the input signal to one that will pass easily through the waveguide 230, transformer 235B which transforms the signal exiting from

waveguide 233 to a form suitable to be used by the external wave ide (not shown), and polarizers 236A and 236B which polarize the signal as it enters and depolarizes it as it exits the waveguide 233. In this embodiment the waveguide 233 comprises a delay/shift element 216A which includes a first conductor 219A, a second conductor 221A, and BST layer 218A. Wires 238A and 238B provide a means for connecting conductors 219A and 221A respectfully to delay shift controller 223 (shown in FIG. 2). Varying the voltage across conductors 219A and 221A by means of controller 223 changes the dielectric constant of BST layer 218A and thus the delay and/or phase of the signal traveling in waveguide 233, thereby tuning the signal. In the delay/shift device 230 the barium strontium titanate 218A comprises a dielectric within a distributed capacitance in the transmission line 233.

FIG. 29 shows a microwave/millimeter wave delay/shift device 250 utilizing a delay/shift elements 216B through 216E according to the invention in which the wavelength of the signal being processed is of much larger than the electronic components. The device 250 comprises a signal input 252 which couples a signal to be processed to the device 250, a transmission line 253, which would generally be called a circuit 253 in this embodiment, and a signal output 254 which couples the signal output by device 250 to and external circuit (not shown). Transmission line 253 comprises a lumped circuit of variable capacitors 216B through 216E and inductors 256; such a circuit is sometimes referred to as an "artificial" transmission line. Each of the variable capacitors 216B through 216E is a delay/shift element such as 216 in FIG. 25 having a variable voltage source, such as 23 in FIG. 25 Tuning the variable capacitors 216B through 216E changes the dielectric constant of the capacitors and thus tunes the transmission line 253 to delay and/or phase shift the signal passing along it, thereby tuning the signal.

If either of devices 230 or 250 is implemented as a microwave integrated circuit (MIC) or other micro device, the transmission lines 233 and/or 253 may be implemented as a microstrip device 240 as shown in FIG. 28 Microstrip device 240 comprises a ground plane 219B which is the first conductor in device 240, microstrip 221B which acts as the second conductor, and BST layer 218B separating the conductors. In this case the delay shift controller 223 (FIG. 26) applies a variable voltage across ground plane 219B and microstrip 221B to vary the dielectric constant

of BST layer 218B.

Turning now to FIGS 30-33, test devices 60, 70 and 80 for testing the BST material according to the invention are shown. FIG. 30 shows a capacitor device 260 for measuring the bulk capacitance of the BST material according to the invention. It comprises a first conductive electrode 264 in the form of a semi-circular thin plate and a second conductive electrode 266 in the form of a semi-circular thin plate separated by a thin strip 262 of BST. A variable bias voltage source 268 applies a voltage to electrodes 264 and 266 to create a variable electric field across BST strip 62.

FIG. 31 shows an interdigitated thin film capacitor device 270 used for measuring the thin film properties of the BST material according to the invention. It comprises a first conductive electrode 274 and a second conductive electrode 76 which have fingers, such as 273 and 277 respectively, which intermesh and are separated by a thin strip 272 of BST. The electrodes 274 and 276 and the BST strip 272 are thin films formed on a substrate 279. A variable bias voltage source 78 applies a voltage to electrodes 274 and 276 to create a variable electric field across BST strip 272.

FIGS. 32 and 33 show a coplanar waveguide phase shifter element 280 according to the invention which was used to test the usefulness of the BST material of the invention in a phase shifter. Phase shifter element 280 comprises a first thin film conductor 284 and a second thin film conductor 286 formed on a substrate 289. First thin film conductor 284 is formed in two parts 284A and 284B. The conductors 284 and 286 are formed by depositing a film on substrate 289 and etching it to form a gap 287 in the form of a funnel 287A and 287B at each end connected by a thin linear section 287C. Gap 287 is formed in two parts 287D and 287E separated by conductor 286. A film 282 of BST is then deposited in the gap portions 287D and 287E. The BST film overlies the conductors 284 and 286 on either side, as can best be seen in FIG. 33, although this overlap is merely a fabrication artifact to ensure that the gap portions 287D and 287E are filled. In this embodiment the signal input means 226 is a coaxial cable having an inner conductor 292 and an outer conductor 294. The inner conductor 292 is connected to the second conductor 286, while the outer conductor is connected to the portions 284A and 284B of first conductor 284. Likewise the signal

output means 227 is a coaxial cable 295 having an inner conductor 296 connected to the second conductor 286 and an outer conductor 298 connected to first conductor portions 284A and 284B. In the tests described below, a delay/shift controller 223 (FIG. 26) comprising a variable bias voltage source was used to apply a DC voltage across conductors 284 and 286 via coaxial cable 290 to create an electric field across BST film 282, which DC voltage and field was varied to change the dielectric constant of the film 282 and thereby shift the phase of a signal passing through the coplanar waveguide phase shifter element 280, thereby tuning the signal.

Turning now to FIG. 34, capacitance versus temperature curves for five electric field strengths for a BST capacitor as shown in FIG. 30 are shown. The sample capacitor 260 had a thickness, t, of 0.71 mm, a diameter, D, of 0.8 cm, and a BST strip 262 width, d, of 0.08 mm. The electrodes 264 and 266 were made of YBCO superconductor and the BST was $Ba_{0.1}Sr_{0.9}TiO_3$. Electric fields of 0 kV/cm, 3.125 kV/cm, 6.25 kV/cm, 12.5 kV/cm, and 25 kV/cm provided by voltage source 68 were placed across the capacitor 260 and the capacitance in picofarads was measured at a frequency of 100 kHz at the points shown as the temperature ranged from approximately 40 K to 150 K. Each of the curves peaked at between 86 K and 88 K, with the peak moving to a higher temperature as the field increased. The peak capacitance decreased from about 2690 pf at 0 kV/cm to about 450 pf at 25 kV/cm. This represents a change of about 500%. This change is enormous compared to the 16% to 50% changes reported in the Varadan article cited above and the changes of 10% to 20% reported to be feasible in the Jackson paper entitled "Novel Monolithic Phase Shifter Combining Ferroelectrics and High Temperature Superconductors" cited above.

FIG. 35 shows capacitance versus temperature curves for five electric field strengths for a $Ba_{0.09}Sr_{0.91}TiO_3$ capacitor as shown in FIG. 30. The sample capacitor 260 had a thickness, t, of 1.05 mm, a diameter, D, of 2.12 cm, and a BST strip 262 width, d, of 0.08 mm. The electrodes 264 and 266 were made of YBCO and the BST was $Ba_{0.09}Sr_{0.91}TiO_3$. Electric fields of 0 kV/cm, 3.125 kV/cm, 6.25 kV/cm, 12.5 kV/cm, and 25 kV/cm were placed across the capacitor 260 and the capacitance in picofarads was measured at a frequency of 100 kHz at the points shown as the temperature ranged from approximately 46 K to 120 K. Each of the curves peaked

the bulk devices in the prior art. Thus, for the first time, the tuneability of the material is large enough for a practical MIC delay line or phase shifter.

FIG. 37 shows capacitance versus temperature curves for four voltages for a $Ba_{0.08}Sr_{0.92}TiO_3$ thin film capacitor as shown in FIG. 31 which capacitor was the same as that described above except the width of the fingers 273, 277 and the BST strip 272 was about 4500 Å. Thus this capacitor was about 60% of the size of the capacitor of FIG. 36. The figure also shows a single point on the capacitance/temperature curve for three other voltages. Voltages of 0 V, 5 V, 10 V, and 20 V were placed across the capacitor 270 and the capacitance in picofarads was measured at a frequency of 100 kHz at the points shown as the temperature ranged from approximately 40 K to 300 K. Each of the curves peaked at about 82 K, with little evident shift of the peak as the field increased. Points were also obtained for the capacitance at 82 K for voltages of 30 V, 40 V, and 50 V. The peak capacitance decreased from about 6.67 pf at 0 kV/cm to about 5.96 pf at 66 kV/cm. The percent change of the capacitance for each of the peak capacitance values is shown for each curve and the individual test points for the 30V - 50 volt measurements. The maximum change is about 10.7%.

FIG. 38 shows loss tangent versus temperature curves for the same capacitor, electric field strengths, and frequency used in obtaining the curves of FIG. 36. The curves show that the loss tangent has a local minimum at about the same temperature as the peak capacitance. Overall the loss tangent is in the range of about 2×10^{-2} and 4×10^{-2} which is about the range reported for prior art GaAs tuneable microwave devices which generally are utilized with normal conductors rather than superconductors. Thus the BST delay/shift elements 223 can be used with or without the superconducting electrodes. Since the largest change in the dielectric constant is in the temperature range of the high temperature superconductors, the use of superconductors as the conductors 219, 221 etc. is preferable, though this is not necessary.

FIG. 39 shows the measured change of phase angle and effective dielectric constant versus electric field strength for the phase shifter of FIGS. 32 and 33. The conductors 284A, 284B, and 286 were made of YBCO, the BST was $Ba_{.08}Sr_{0.92}TiO_3$, and the substrate 289 was made of lanthanum aluminate. The length of the phase

at between 78 K and 81 K, with the peak moving to a higher temperature as the field increased. The peak capacitance decreased from about 4150 pf at 0 kV/cm to about 1600 pf at 25 kV/cm. This represents a change of about 150% which is significantly smaller than the change for the $Ba_{0.1}Sr_{0.9}TiO_3$ sample discussed above, but still enormous compared to the prior art. The primary cause for the difference is believed to be due to the 1% change in the BST composition. This indicates that the delay/shift element 216 can not only be tuned by the applied voltage, but the composition can also be "tuned" to provide the desired delay or phase shift. This is very important in the microwave area where matching parameters is critical. Comparing FIGS. 34 and 35, it is evident that as one reduces the barium content and increases the strontium content the peak goes to smaller temperatures. Thus the delay/shift element 216 can also be "tuned" to a desired phase or delay by varying the temperature.

FIG. 36 shows capacitance versus temperature curves for six electric field strengths for a $Ba_{0.08}Sr_{0.92}TiO_3$ thin film capacitor as shown in FIG. 31. The width of the fingers 273, 277, i.e. the dimension in the vertical direction in FIG. 31 was 7600 Å, which was also the thickness of the BST strip 272. The thin film was about 6000Å thick, i.e. in the direction out of the paper in FIG. 31, the electrodes 274 and 276 were made of YBCO and the substrate 279 was lanthanum aluminate. Electric fields of 0 kV/cm, 13 kV/cm, 26 kV/cm, 39 kV/cm, 53 kV/cm, and 66 kV/cm were placed across the capacitor 270 and the capacitance in picofarads was measured at a frequency of 100 kHz at the points shown as the temperature ranged from approximately 20 K to 300 K. Each of the curves peaked at between 70 K and 90 K, with the peak moving to a higher temperature as the field increased. The peak capacitance decreased from about 6.5 pf at 0 kV/cm to about 5.9 pf at 66 kV/cm. This represents a change of about 10% which is significantly smaller than the change for the bulk samples discussed above, but still is about the same size as the change for the bulk samples described in the prior art. The primary cause for the difference is believed to be due to the thin film. That is, in the thin material surface effects, such as surface charges, predominate. Since it is expected that the bulk results published in the prior art would decrease similarly, the result of FIG. 36 is a true breakthrough, since the thin film results are nearly equal to the results for

shifter waveguide, i.e. the distance across the conductors 21 and 286 in the horizontal direction in FIG. 32 was about 13 mm, the thickness of the BST 282 in each of gap portions 287D and 287E in the horizontal direction in FIG. 33 was about 5 microns and the thickness of the conductors films 284A, 284B, and 286, respectively in the vertical direction in FIG. 33 was about 6000 Å. The phase shift was measured in units of π at a frequency of 10 GHz (gigahertz) using a Hewlett Packard model HP8510 Network Analyzer. The results show a change of about .7π or 126 degrees over a change of field from 0 kV/cm to 6 kV/cm. Typically, in phase shifters one seeks to have changes of about 90 degrees or more, so the phase shift is well within the range of a practical device. Over the same range of field strengths, the dielectric constant changes from about 14.5 to about 25 or about 30%.

The BST and other thin films of the invention can be made by methods including physical vapor deposition, chemical vapor deposition, laser deposition, sputtering, sol gel processing, and many other processes and can be patterned by many known MIC patterning processes, such as ion milling, chemical etching, etc. In particular the YBCO of the devices of FIGS 30, 31 and 32 was deposited by laser ablation, while the BST was deposited by a sol-gel process. The devices were patterned using a chemical wet etch. These processes are all well-known in the art and thus will not be discussed in detail herein.

There has been described a novel tuneable dielectric constant electronic device utilizing a thin film BST material having a dielectric constant that is far more tuneable than prior art BST devices. It should be understood that the particular embodiments shown in the drawings and described within this specification are for purposes of example and should not be construed to limit the invention which will be described in the claims below. Further, it is evident that those skilled in the art may now make numerous uses and modifications of the specific embodiments described, without departing from the inventive concepts. For example, now that a BST material having such large tuneability is disclosed, many other applications of the material can be made. Equivalent structures and process may be substituted for the various structures and processes described. Additional features and thin film layers may be added. Or a variety of different dimensions and conductor materials may be used. Many other variations are possible.

The advantages of the present invention, as well as certain changes and modifications of the disclosed embodiments thereof, will be readily apparent to those skilled in the art. It is the applicants' intention to cover in their claims all those changes and modifications which could be made to the embodiments of the invention herein chosen for the purpose of the disclosure without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A tuneable electrical component comprising a thin film of ferroelectric material, the dielectric property of the ferroelectric thin film being a function of a voltage applied to the ferroelectric thin film, the ferroelectric thin film being adapted to be connected to a circuit which is to be tuned in response to the dielectric property of the thin film of ferroelectric thin film, and a thin film of superconductive material contiguous with the surface of the ferroelectric thin film, the superconductive thin film being adapted to apply a voltage to the ferroelectric thin film to determine the dielectric property thereof.

2. A tuneable electrical component in accordance with claim 1 in which the thin film of ferroelectric material is deposited on a surface of the thin film of superconductive material which is a high temperature superconductive material. a. A tuneable electrical component in accordance with claim 1 in which the thin film of superconductive material is deposited on a surface of the ferroelectric thin film is a thin film of high temperature superconductive material.

3. A tuneable electrical component in accordance with claim 1 and further comprising a substrate contiguous with one of the ferroelectric thin film and the superconductive thin film to support the same.

4. A tuneable electrical component in accordance with claim 6 in which the substrate is formed of crystalline material.

5. A tuneable electrical component in accordance with claim 1 and further comprising means for applying a predetermined voltage to the superconductive thin film.

6. A tuneable electrical component in accordance with claim 1 and further comprising means for applying a variable voltage to the ferroelectric thin film to vary the dielectric property of the ferroelectric thin film.

7. A tuneable electrical antenna component in accordance with claim 1 and further comprising an additional thin film of superconductive material deposited on the surface of the ferroelectric thin film disposed opposite to the surface thereof upon which the superconductive thin film is disposed.

8. A tuneable electrical phase shifter comprising a thin film of ferroelectric material, the dielectric property of the ferroelectric thin film being a function of a voltage applied to the ferroelectric thin film, the ferroelectric thin film being adapted to be connected to a circuit which is to be tuned in response to a phase shift resulting from the dielectric property of the thin film of ferroelectric thin film, and a thin film of superconductive material deposited on a surface of the ferroelectric thin film, the superconductive thin film being adapted to apply a voltage to the ferroelectric thin film to determine the dielectric property and thereby the phase shift thereof.

9. A tuneable electrical phase shifter in accordance with claim 9 and further comprising means for applying a predetermined voltage to the superconductive thin film and thereby to the ferroelectric thin film to determine the dielectric property of the ferroelectric thin film.

10. A tuneable electrical phase shifter in accordance with claim 10 and further comprising means for applying a variable voltage to the superconductive thin film and thereby to the ferroelectric thin film to vary the dielectric property of the ferroelectric thin film.

11. A tuneable electric antenna component for passing radio frequency energy comprising an elongated base portion of ferroelectric material, the dielectric property of the ferroelectric material being a function of a voltage applied to the ferroelectric material, a plurality of elements extending from the base portion and spaced apart from one another at a predetermined interval along the length of the base portion, the predetermined interval between each of the plurality of elements providing a predetermined time delay for radio frequency energy as a function of the dielectric property of the base portion, the predetermined time delay between each of the plurality of elements causing the radio frequency energy to be passed at a common predetermined angle with respect to each of the plurality of elements.

12. A tuneable electric antenna component for passing radio frequency energy in accordance with claim 12 in which the height of each of the plurality of elements being a fraction of the width of the base portion in the direction in which the plurality of elements extend.

13. A tuneable electric antenna component for passing radio frequency energy in accordance with claim 12 in which the radio frequency energy is microwave energy.

14. A tuneable electric antenna component for passing radio frequency energy in accordance with claim 12 in which the dielectric property of the ferroelectric material of the base portion which is a function of a voltage applied to the ferroelectric material is the dielectric constant of the ferroelectric material of the base portion.

15. A tuneable electric antenna component for passing radio frequency energy in accordance with claim 12 in which the plurality of elements extending from the base portion and spaced apart from one another at a predetermined interval along the length of the base portion are of ferroelectric material, the dielectric property of the ferroelectric material is a function of a voltage applied to the ferroelectric material.

16. A tuneable electric antenna component for passing radio frequency energy in accordance with claim 12 and further comprising means for applying a predetermined voltage to the base portion of the ferroelectric material to determine the dielectric property of the antenna component, the means for the dielectric property of the antenna component and the interval between the elements extending from the base portion being adapted to produce the predetermined time delay causing the radio frequency energy to be passed at a common predetermined angle with respect to each of the plurality of elements.

17. A tuneable electric antenna array comprising a plurality of tuneable electric antenna components for passing radio frequency energy, each component having an elongated base portion of ferroelectric material, the dielectric property of the ferroelectric material being a function of a voltage applied to the ferroelectric material, a plurality of elements extending from the base portion and spaced apart from one another at a predetermined interval along the length of the base portion, the predetermined interval between each of the plurality of elements providing a predetermined time delay for radio frequency energy applied to the base portion as a function of the dielectric property of the base portion, the predetermined time delay between each of the plurality of elements causing the radio frequency energy to be passed at a common predetermined angle with respect to each of the plurality of elements, each of the plurality of components being disposed in a common plane with the base portion thereof positioned parallel to one another with a predetermined distance between each base portion corresponding to an additional predetermined time delay for causing the radio frequency energy to be passed at an additional common predetermined angle with respect to the length of the base portion of each component, and means for applying a biasing voltage to the base portion of each of the plurality of components to control the additional common predetermined angle.

18. A tuneable electric antenna array in accordance with claim 18 and further comprising means for applying a predetermined voltage to cause the radio frequency energy to be passed at a common predetermined angle with respect to each of the plurality of elements of each component of the plurality components of the antenna array.

19. A tuneable electric antenna array in accordance with claim 18 in which the array includes an additional plurality of tuneable electric antenna components and in which the means for applying a biasing voltage to the base portion of each of the plurality of components applies the biasing voltage to the components of the array and the additional array.

20. A phased array antenna comprising a plurality of antenna elements for passing radio frequency energy, a plurality of phase shifters with each phase shifter having a thin film of ferroelectric material, the dielectric property of the ferroelectric thin film being a function of a voltage applied to the ferroelectric thin film, the ferroelectric thin film of each phase shifter being connected to a different one of the plurality of antenna elements and to a source of radio frequency energy, a layer of superconductive material deposited on a surface of the ferroelectric thin film of each phase shifter, the superconductive thin film being adapted to apply a voltage to the ferroelectric thin film upon which it is deposited to determine the dielectric property thereof and thereby the phase shift of each phase shifter.

21. A phased array antenna in accordance with claim 21 and further comprising means for applying a predetermined voltage to the ferroelectric thin film of each of the plurality of phase shifters to determine the phase shift of the radio frequency energy being connected to the antenna element by the ferroelectric thin film.

22. A phased array antenna in accordance with claim 21 and further comprising means for applying a variable voltage to the ferroelectric thin film of each of the plurality of phase shifters to vary the phase shift of the radio frequency

energy being connected to the antenna element by the ferroelectric thin film.

23. A tuneable superconducting fringe effect capacitor comprising a thin film of ferroelectric material having a dielectric property which is a function of a voltage applied thereto, and a pair of thin films of superconductive material deposited on the ferroelectric film with a predetermined space therebetween, the thin films of superconductive material providing a capacitive function with the film of ferroelectric material in the predetermined space between the thin films of superconductive material.

24. A tuneable superconducting fringe effect capacitor in accordance with claim 24 and further comprising means for applying a voltage across the superconductive films and thereby to the ferroelectric film in the predetermined space between the superconductive films to affect the dielectric property of the ferroelectric film and thereby the capacitance of the capacitor.

25. A tuneable superconducting fringe effect capacitor in accordance with claim 24 and further comprising means for applying a variable voltage across the superconducting films and thereby to the ferroelectric film in the predetermined space between the superconductive films to vary the dielectric property of the ferroelectric film and thereby the capacitance of the capacitor.

26. A tuneable superconducting fringe effect capacitor in accordance with claim 24 and further comprising a substrate, the surface of ferroelectric film disposed opposite to the surface thereof upon which the pair of superconductive thin film are deposited being contiguous with the surface of the substrate.

a. A tuneable coplanar electrical component comprising a thin film of dielectric material and a plurality of lines of thin films of

superconductive material deposited on the thin film of dielectric material, the dielectric material having a dielectric property which is a function of voltage applied thereto.

27. A tuneable coplanar electrical component in accordance with claim 28 in which the plurality of lines are spaced apart and parallel with respect to one another.

28. A tuneable coplanar electrical component in accordance with claim 28 which a line of superconductive thin film disposed spaced apart and parallel to the lines of the plurality of lines adjacent thereto is interrupted to form a portion of a line the dimensions of which provide a resonant circuit with respect to the lines of the plurality adjacent thereto.

29. A capacitively coupled microstrip resonator comprising strip of superconductive material, a pair of additional strips of superconductive material, and means connecting to each of the pair of additional strips of superconductive material to the strip of superconductive material for providing a voltage thereto.

30. A tuneable capacitively coupled microstrip resonator comprising a pair of strips of superconductive material, each strip having an end portion disposed in a facing relationship to the end forming a gap between the end portions, a strip of ferroelectric material extending across the gap in contact with the end portion of the superconductive lines, means connected to each of the pair of strips of superconductive material for providing a voltage thereto and thereby to the strip of ferroelectric material to determine the dielectric property of the strip dielectric material and thereby to tune the resonator.

31. A tuneable capacitively coupled microstrip resonator in accordance with claim 32 in which the means connected to each of the pair of strips of superconductive material for providing a voltage thereto further comprises an additional strip of superconductor connected to the pair of strips of superconductive material.

32. A tuneable superconducting fringe effect capacitor comprising a thin film of ferroelectric material having a dielectric property which is a function of a voltage applied thereto, and a pair of thin films of superconductive material deposited on the ferroelectric film with a predetermined space therebetween, the predetermined space being formed by a plurality of projections extending from each of the pair of thin films of superconductive material and nested with respect to one another, the thin films of superconductive material providing a capacitive function with the film of ferroelectric material in the predetermined space formed by the nested projections between the thin films of superconductive material.

33. A tuneable superconducting fringe effect capacitor in accordance with claim 34 and further comprising means for applying a voltage across the pair of superconductive thin films and thereby to the ferroelectric film in the predetermined space between the pair of superconductive thin films to affect the dielectric property of the ferroelectric film and thereby the capacitance of the capacitor.

34. A tuneable superconducting fringe effect capacitor in accordance with claim 34 and further comprising a substrate, the surface of ferroelectric film disposed opposite to the surface thereof upon which the pair of superconductive thin films are deposited being contiguous with the surface of the

substrate.

35. A tuneable superconducting fringe effect capacitor in accordance with claim 34 in which the thin film of ferroelectric material having a dielectric property which is a function of a voltage applied thereto has a portion thereof extending into the predetermined space formed between the pair of thin films of superconductive material.

36. A tuneable antenna comprising a loop of a thin film of superconductive material, layers of insulating material for supporting the loop, the layers being separated by thin film of conductive material for providing a ground plane, a thin film of superconductive material connected to the loop. A thin film of ferroelectric material disposed contiguous on one surface thereof of superconductive material, and an additional thin superconductor film disposed on the opposite surface of the thin film of ferroelectric material and the thin films of superconductive material forming a capacitor, the application of voltage across the capacitor tuning the capacitance thereof and thereby the frequency of the resonance of the circuit formed by the loop and the capacitor 141.

37. A tuneable antenna in accordance with claim 38 in which the loop is a half-loop.

38. A tuneable antenna in accordance with claim 39 in which the half-loop has a base portion and two leg portions disposed in an L-shape the free end of the longer leg of the L-shaped loop being connected to the capacitor.

39. A tuneable electrical component comprising a thin film of ferroelectric material, the dielectric property of the ferroelectric thin film being a function of a voltage applied to the ferroelectric thin film, the ferroelectric thin film being adapted to be connected to a circuit which is to be tuned in response to the dielectric property of the thin film of ferroelectric thin film, and a plurality of thin films of superconductive material deposited on at least one surface of the ferroelectric thin film, the superconductive thin film being adapted to apply a voltage to the ferroelectric thin film to determine the dielectric property thereof.

40. A tuneable electrical component in accordance with claim 41 in which the plurality of thin films of superconductive material deposited on a surface of the ferroelectric thin film are thin film of high temperature superconductive material.

41. A tuneable electrical component in accordance with claim 41 in which the plurality of thin films of superconductive materials are disposed spaced apart from one another on one surface of the ferroelectric thin film.

42. A tuneable electrical component in accordance with claim 41 in which at least one plurality of thin film of superconductive material are deposited on each of the opposite surface of the ferroelectric thin film.

a first electrode made of conventionally conductive material;

a thin film of a dielectric material having a dielectric constant that varies with the electric field applied to said material, said thin film of dielectric material electrically contacting said first electrode;

signal input means for inputting an electrical signal to said dielectric material; and

electrical connecting means for connecting said first electrode to a voltage source for applying an electrical field to said dielectric material to determine the dielectric constant of said material and tune said electrical signal.

44. A tuneable electrical device as in claim 43 wherein said dielectric material comprises a material selected from the group consisting of barium strontium titanate, barium titanate, strontium titanate, lithium niobate, lead strontium titanate, and lead titanate.

45. A tuneable electrical device as in claim 43 wherein said electrode comprises a thin film.

46. A tuneable electrical device as in claim 45 and further including a second electrode, and wherein both of said electrodes comprise a thin film, said thin film of dielectric material has first and second opposing surfaces, said first electrode contacts said first opposing surface, and said second electrode contacts said second opposing surface.

47. A tuneable electrical device as in claim 46 and further comprising a variable voltage source electrically connected to said electrodes via said electrical connecting means.

48. A tuneable electrical device as in claim 43 wherein said dielectric material comprises a ferroelectric material.

49. A tuneable electrical device as in claim 43 wherein said dielectric material comprises barium strontium titanate.

50. A tuneable electrical device as in claim 49 wherein said barium strontium titanate comprises $Ba_xSr_{1-x}TiO_3$ with $0.01 \leq x < 0.2$.

51. A tuneable electrical device as in claim 49 and further comprising temperature control means for maintaining said thin film of barium strontium titanate at a temperature between about 50 K and 110 K.

52. A tuneable electrical device as in claim 43 wherein said temperature control means comprises means for maintaining said thin film of dielectric material at a temperature between about 50 K and 110 K.

53. A tuneable electrical device as in claim 43 wherein said tuneable electrical device comprises a coplanar waveguide phase shifter.

54. A tuneable electrical device as in claim 43 wherein said tuneable electrical device comprises a tuneable fringe effect capacitor.

55. A tuneable electrical device as in claim 43 wherein said tuneable electrical device comprises a transmission line.

56. A tuneable electrical device as in claim 55 wherein said transmission line comprises a distributed capacitance and said dielectric material comprises at least a portion of said distributed capacitance.

57. A tuneable electrical device as in claim 55 wherein said transmission line comprises a waveguide and said dielectric material is located within said waveguide.

58. A tuneable electrical device comprising:

a dielectric material comprising BST material having the formula $Ba_xSr_{1-x}TiO_3$ with $0.01 \leq x < 0.2$;

signal input means for inputting an electrical signal to said BST material; and

electrical bias means for applying an electrical field to said BST material to determine the dielectric constant of said material and tune said electrical signal.

59. A tuneable electrical device as in claim 58 wherein $0.08 \leq x \leq 0.12$.

60. A tuneable electrical device as in claim 59 wherein x equals 0.1.

61. A tuneable electrical device as in claim 58 and further including means for maintaining said BST at a temperature between 50 K and 110 K.

62. A tuneable electrical device as in claim 58 wherein said electrical bias means comprises a thin film of a conducting material and said dielectric material comprises a thin film of said BST in contact with said thin film of conducting material.

63. A tuneable electrical device as in claim 62 wherein said conducting material comprises a superconducting material.

64. A tuneable electrical device as in claim 62 and further comprising a variable voltage source electrically connected to said thin film of conductive material.

65. A tuneable electrical device as in claim 58 wherein said tuneable electrical device comprises a coplanar waveguide phase shifter.

66. A tuneable electrical device as in claim 58 wherein said tuneable electrical device comprises a tuneable fringe effect capacitor.

67. A tuneable electrical device as in claim 58 wherein said tuneable electrical device comprises a transmission line.

68. A tuneable electrical device as in claim 67 wherein said transmission line comprises a distributed capacitance and said BST material comprises at least a portion of said distributed capacitance.

69. A tuneable electrical device as in claim 67 wherein said transmission line comprises a waveguide and said BST material is located within said waveguide.

70. A tuneable electrical device comprising:

a dielectric material;

means for maintaining said dielectric material at a temperature between 67 K and 110 K;

signal input means for inputting an electrical signal to said dielectric material; and

electrical bias means for applying an electrical field to said dielectric material to determine the dielectric constant of said material and tune said electrical signal.

71. A tuneable electrical device as in claim 70 wherein said means for maintaining comprises means for maintaining said temperature at between 70 K and 90 K.

72. A tuneable electrical device as in claim 70 wherein said dielectric material comprises BST.

73. A tuneable electrical device as in claim 72 wherein said dielectric material comprises $Ba_xSr_{1-x}TiO_3$ with $0.01 \leq x < 0.2$.

74. A tuneable electrical device as in claim 70 wherein said electrical bias means comprises first and second conducting layers and said dielectric material is located between said first and second conducting layers.

75. A tuneable electrical device as in claim and further comprising a variable voltage source electrically connected across said first and second conducting layers.

76. A tuneable electrical device as in claim wherein said tuneable electrical device comprises a coplanar waveguide phase shifter.

77. A tuneable electrical device as in claim wherein said tuneable electrical device comprises a tuneable fringe effect capacitor.

78. A tuneable electrical device as in claim wherein said electrical device comprises a transmission line.

79. A tuneable electrical device as in claim wherein said transmission line comprises a distributed capacitance and said BST comprises at least a portion of said distributed capacitance.

80. A tuneable electrical device as in claim wherein said transmission line comprises a waveguide and said BST is located within said waveguide.

81. A tuneable electrical device comprising:

first and second layers of conventionally conductive material;

a thin film of a dielectric material located between said first and second layers of conventionally conductive material, said dielectric material having a dielectric constant that varies with the electric field applied to said material;

signal input means for inputting an electrical signal to said dielectric material; and

means for connecting said first and second layers of conventionally conductive material to a voltage source for applying an electrical field across said first and second layers of conducting material to determine the dielectric constant of said dielectric material and tune said electrical signal.

82. A tuneable electrical device as in claim wherein one of said first and second layers of conventionally conductive material is a thin film.

83. A tuneable electrical device comprising:

a substrate;

first and second thin films of conventionally conductive material carried by said substrate;

a thin film of a dielectric material between said first and second thin films of conventionally conductive material, said dielectric material having a dielectric constant that varies with the electric field applied to said material;

signal input means for inputting an electrical signal to said dielectric material; .and

means for connecting said first and second thin films of conventionally conductive material to a voltage source.

84. A tuneable electrical device as in claim 83 and further comprising a variable voltage means connected to said means for connecting for applying an electrical field across said first and second thin films of conducting material to determine the dielectric constant of said dielectric material and tune said electrical signal.

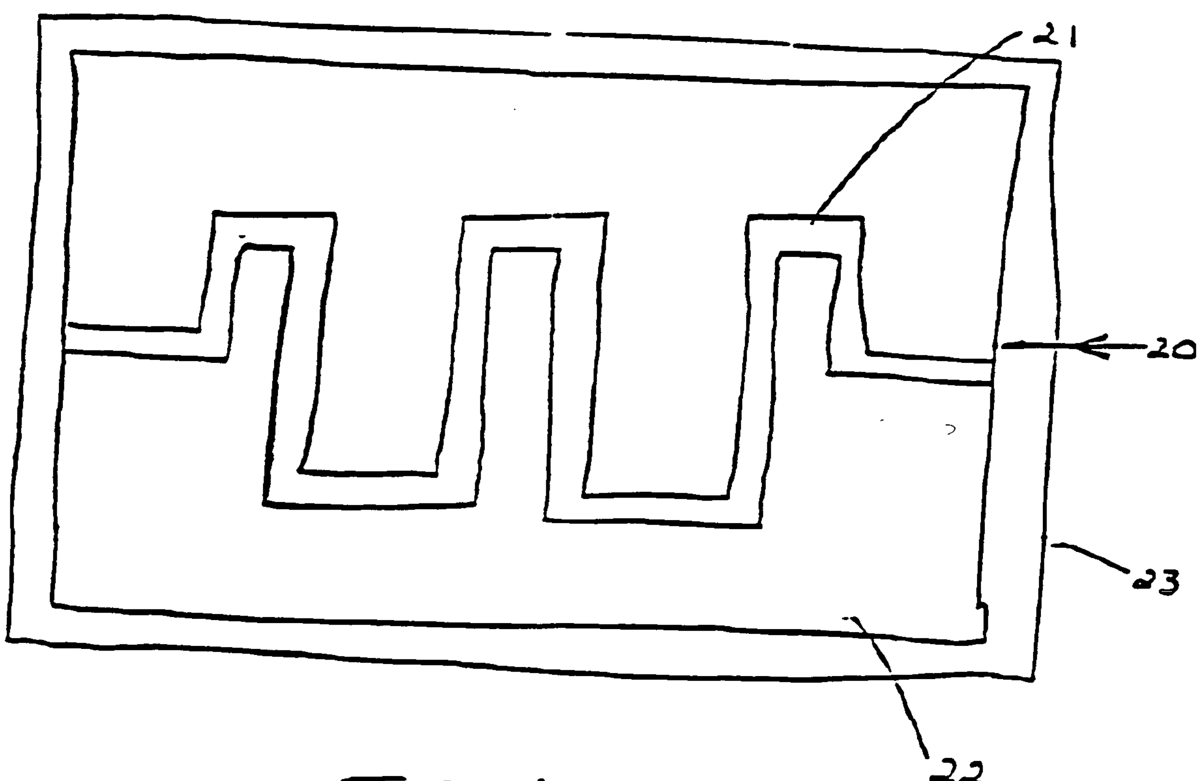


FIG. 1

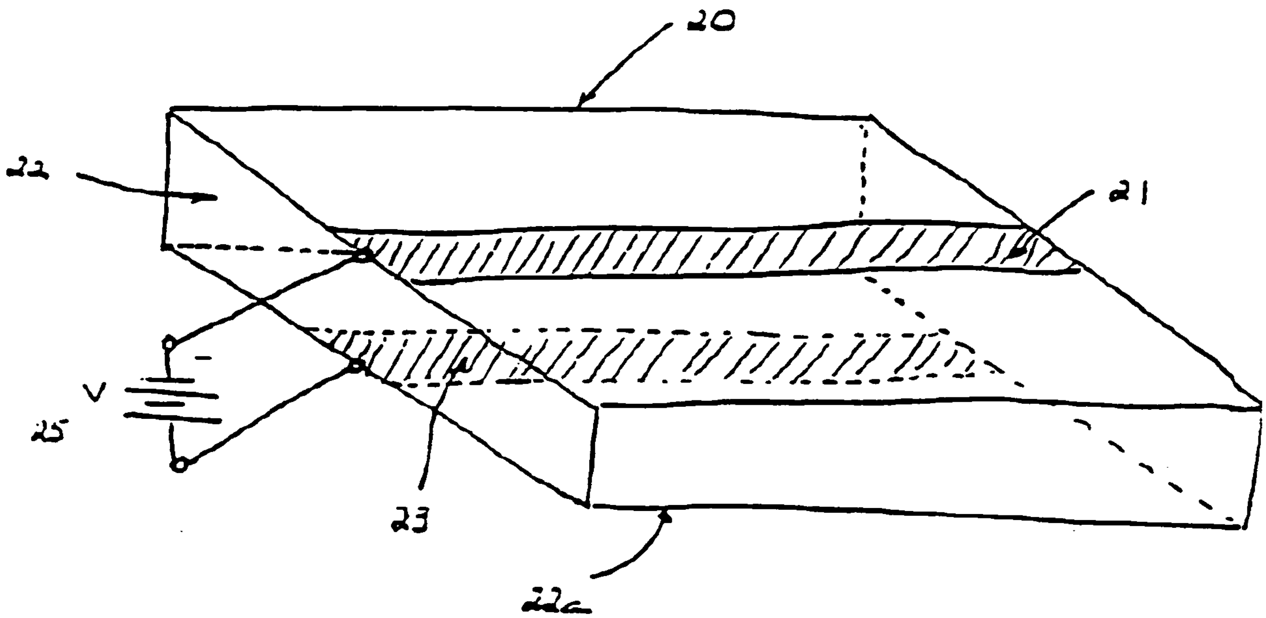


FIG. 2

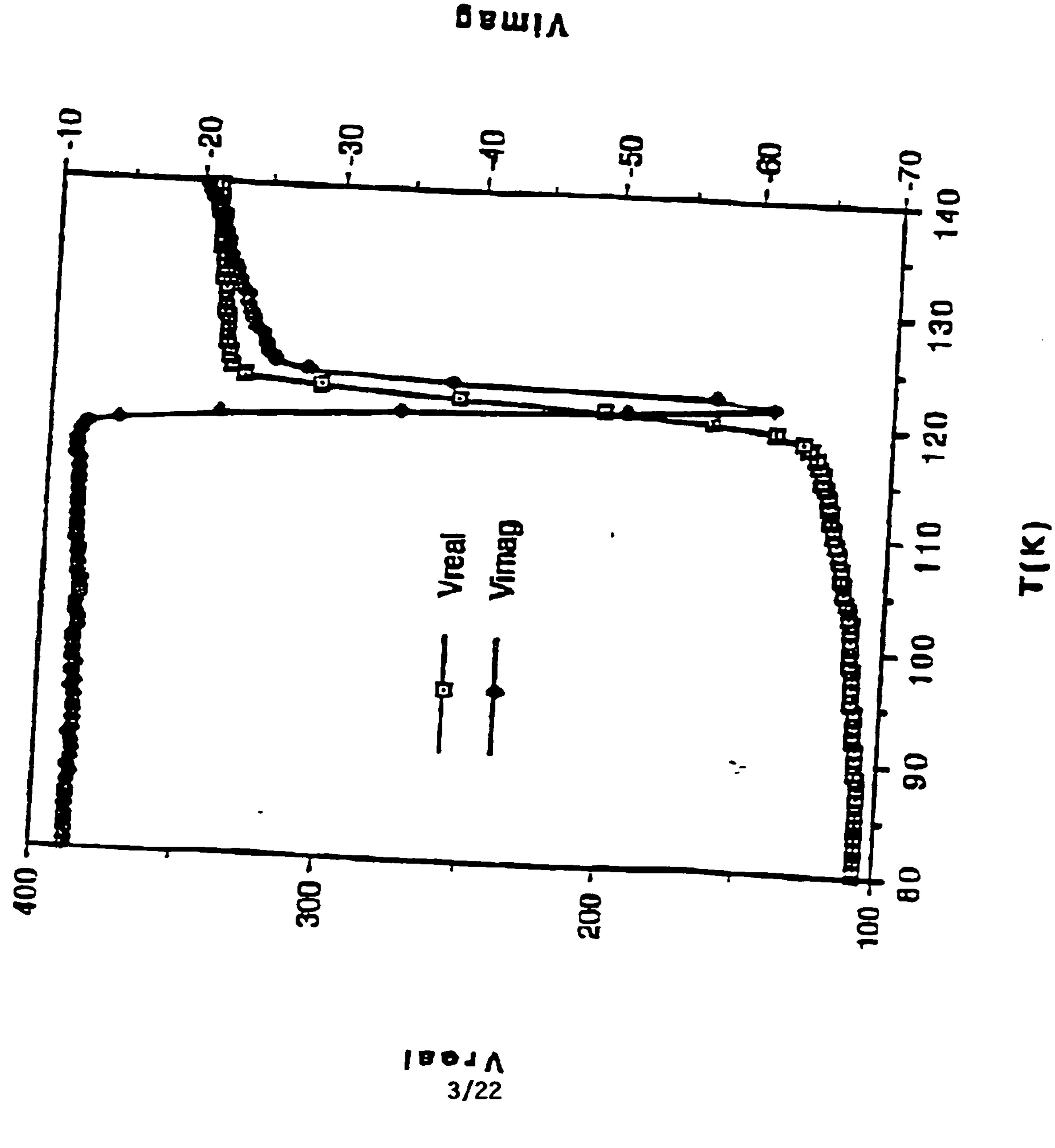

Vimag
-10
-20
-30
-40
-50
-60
-70
Vreal
Vimag
T(K)
80
90
100
110
120
130
140
400
300
200
100
Vreal

FIG. 3

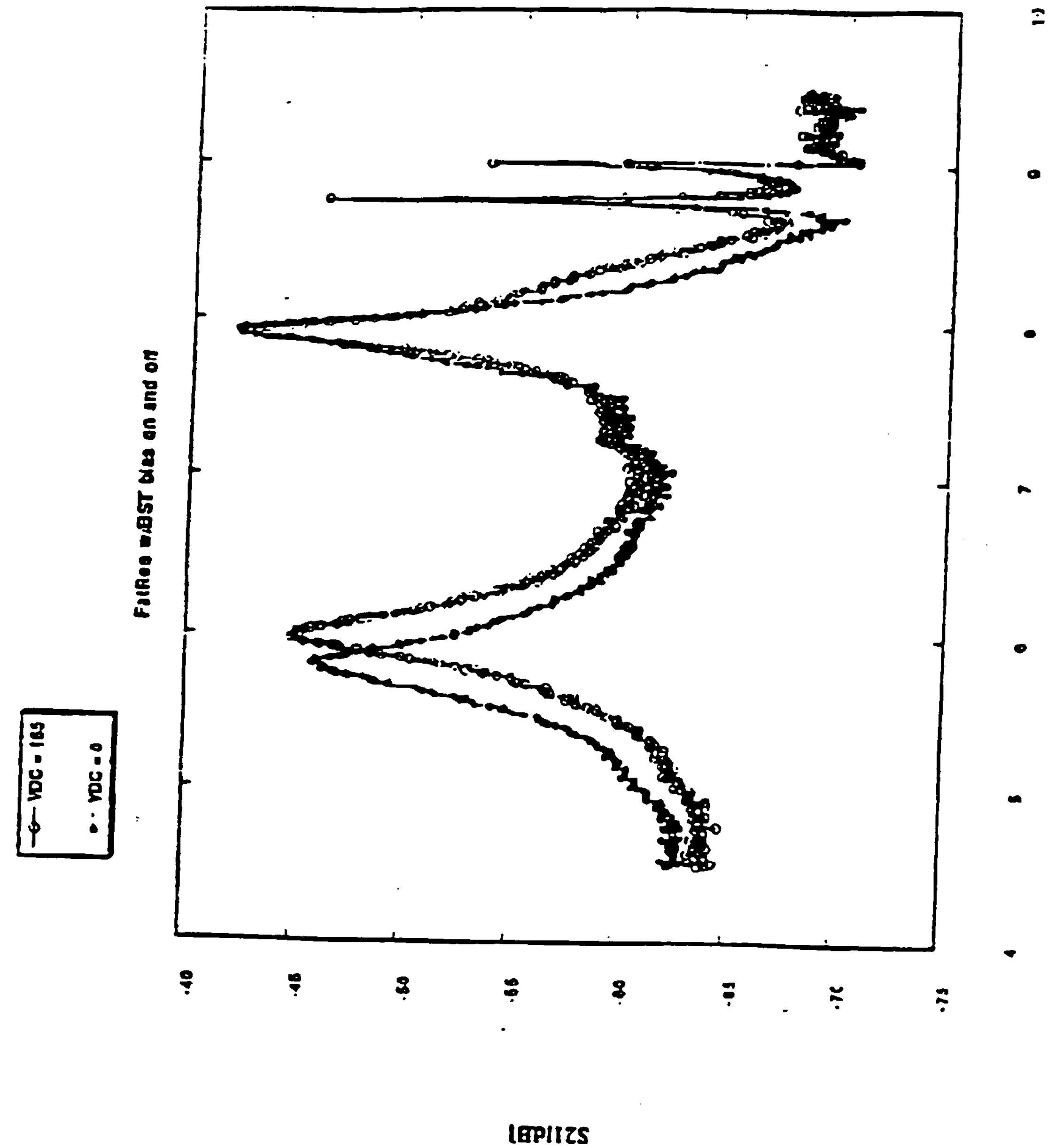


FIG. 4

INSERTION LOSS OF TUNABLE RESONATOR

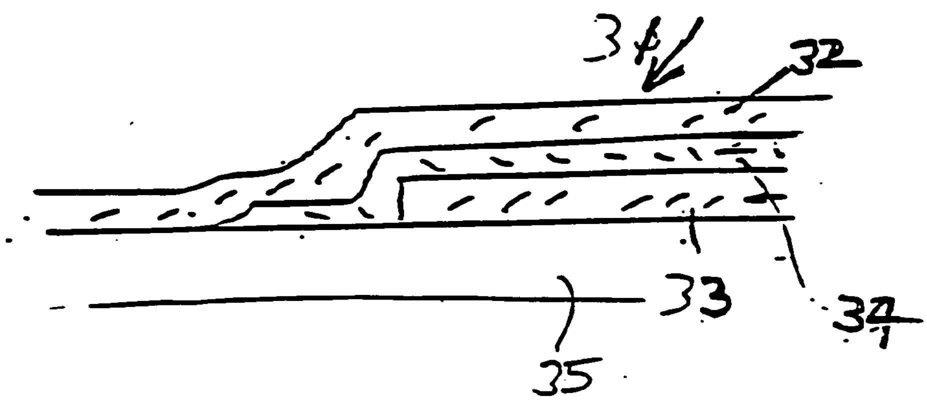


FIGURE 5

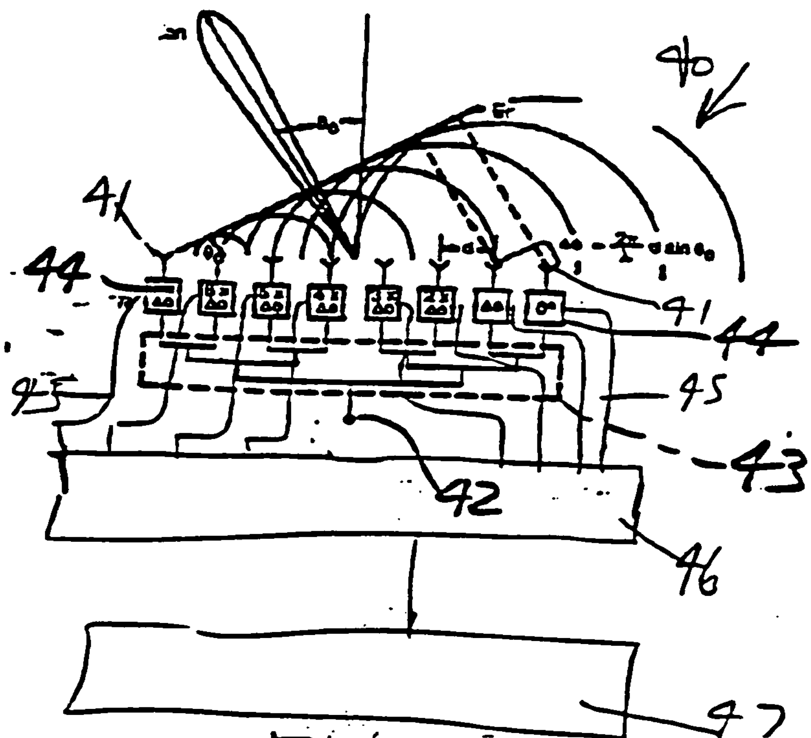


FIG. 6

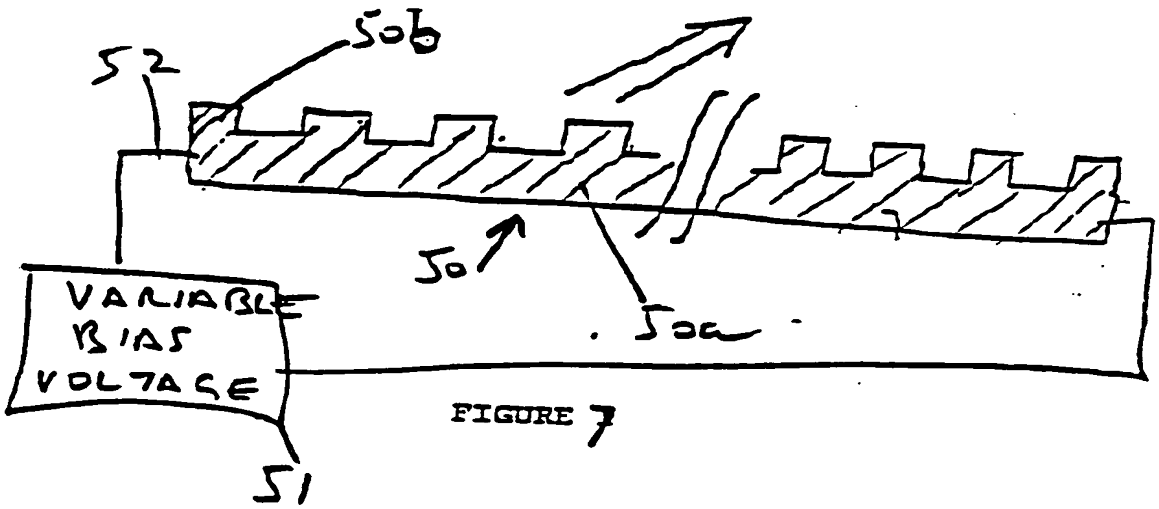


FIGURE 7

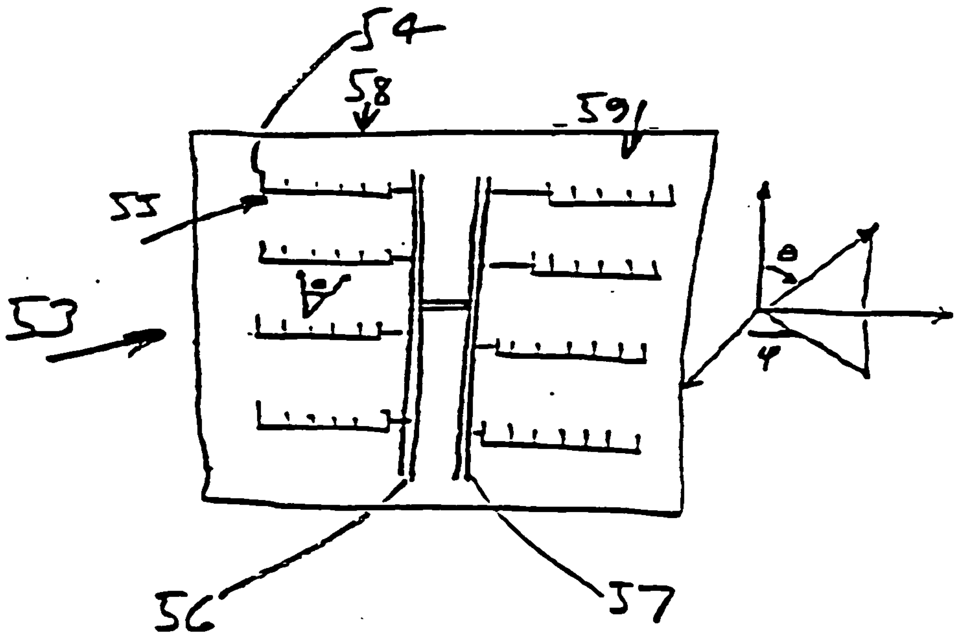


FIGURE 8

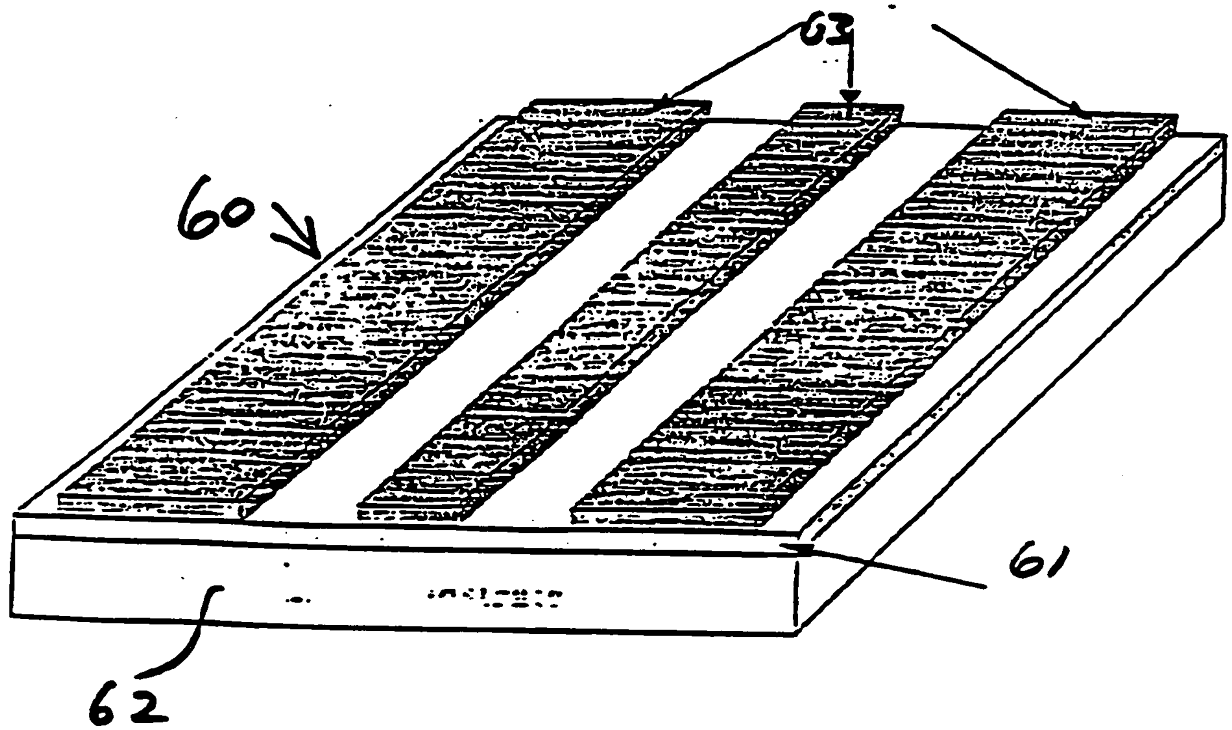


FIGURE 9

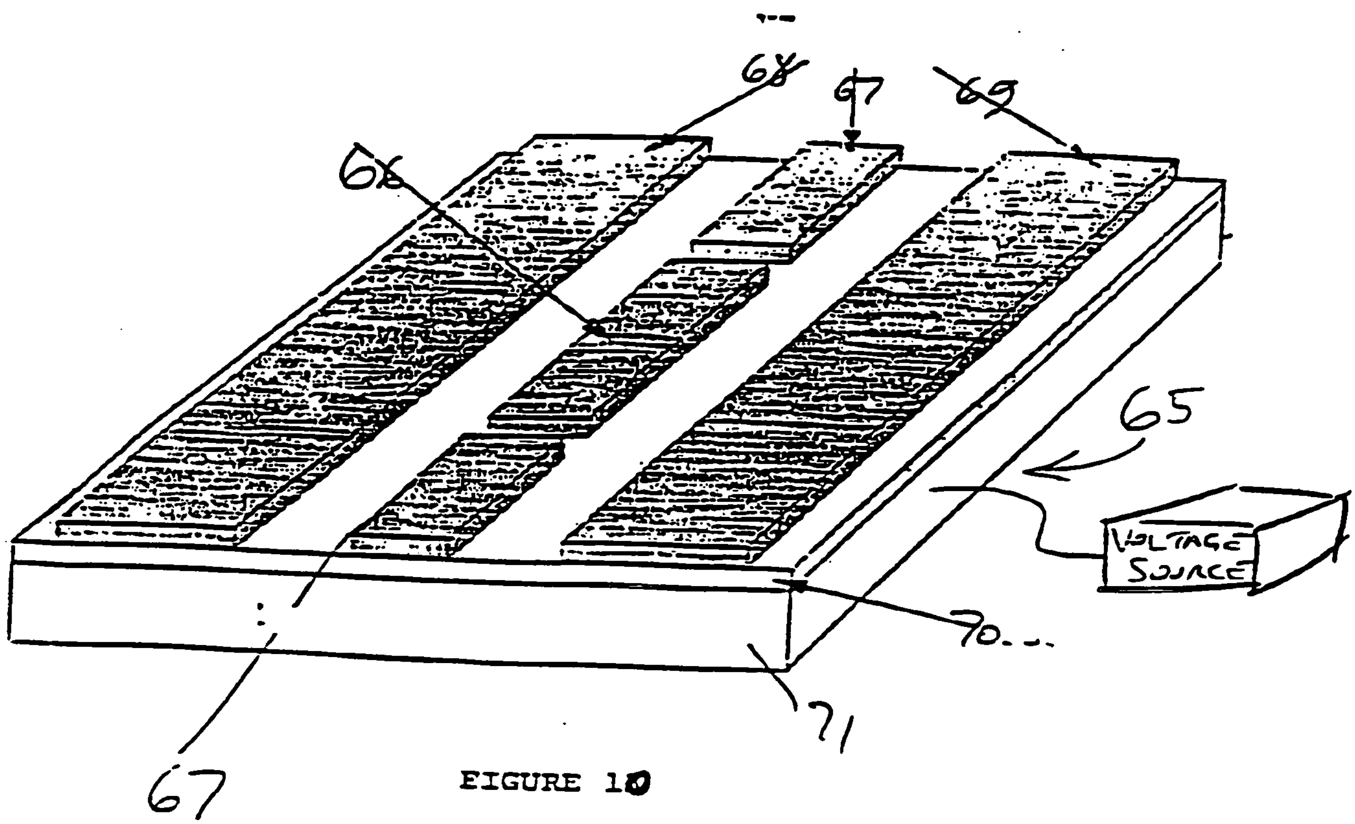


FIGURE 10

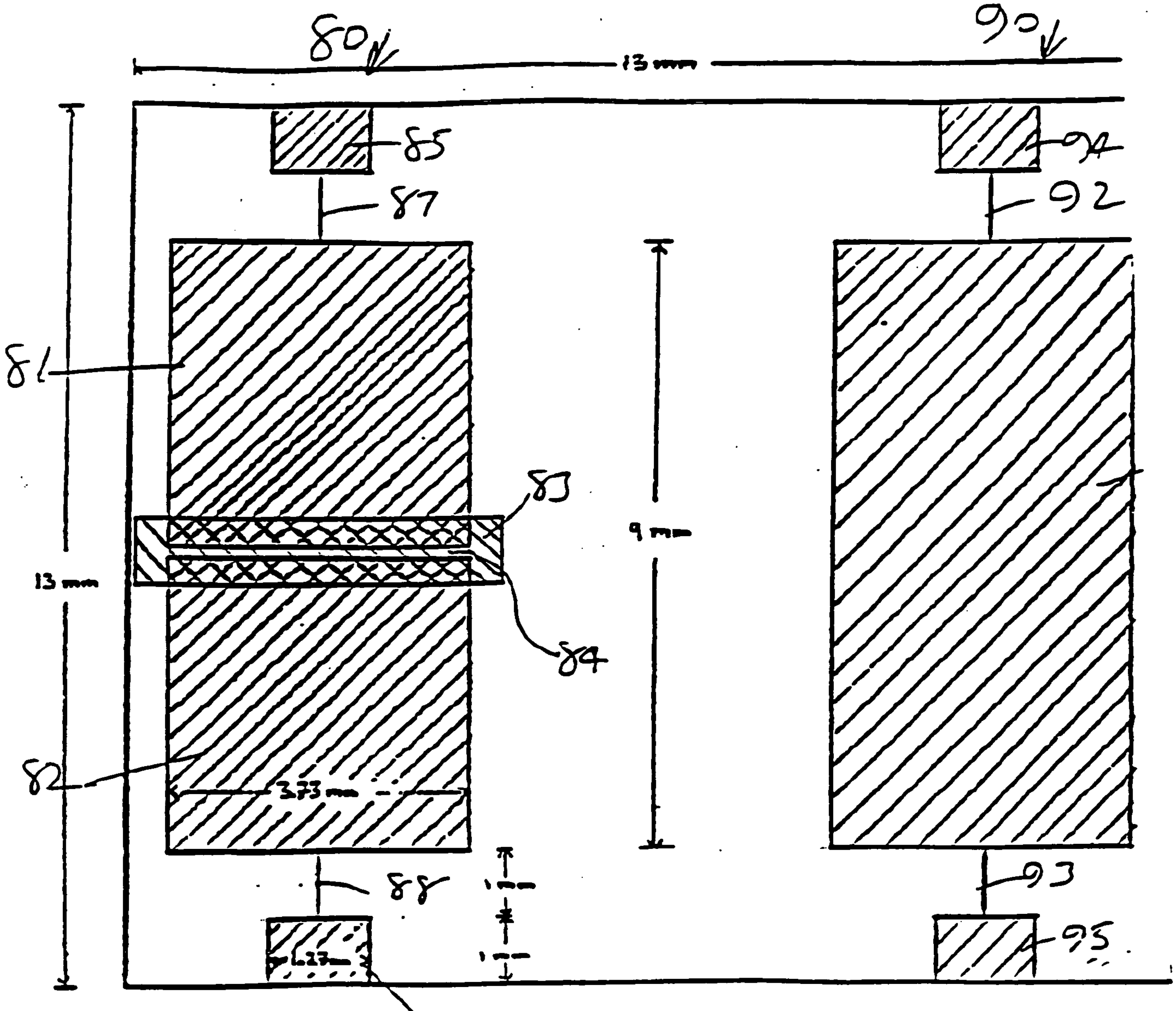

80
90
13 mm
85
94
87
92
81
83
9 mm
13 mm
84
82
3.73 mm
88
93
1 mm
1 mm
95
1.27 mm
86

FIGURE 11


ferroelectric =
= superconductor

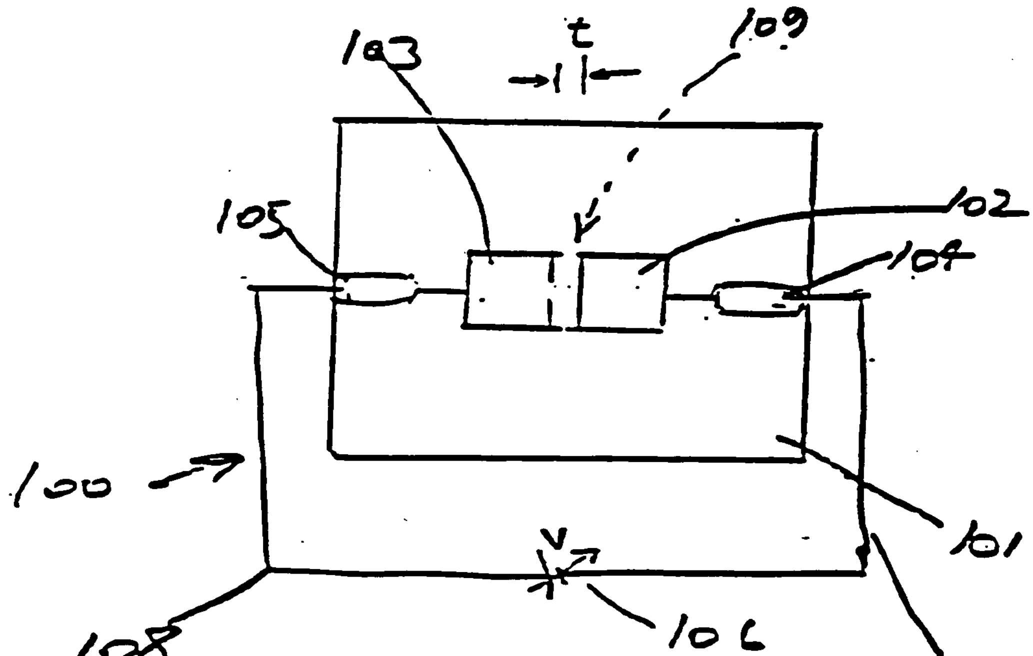


FIGURE 12

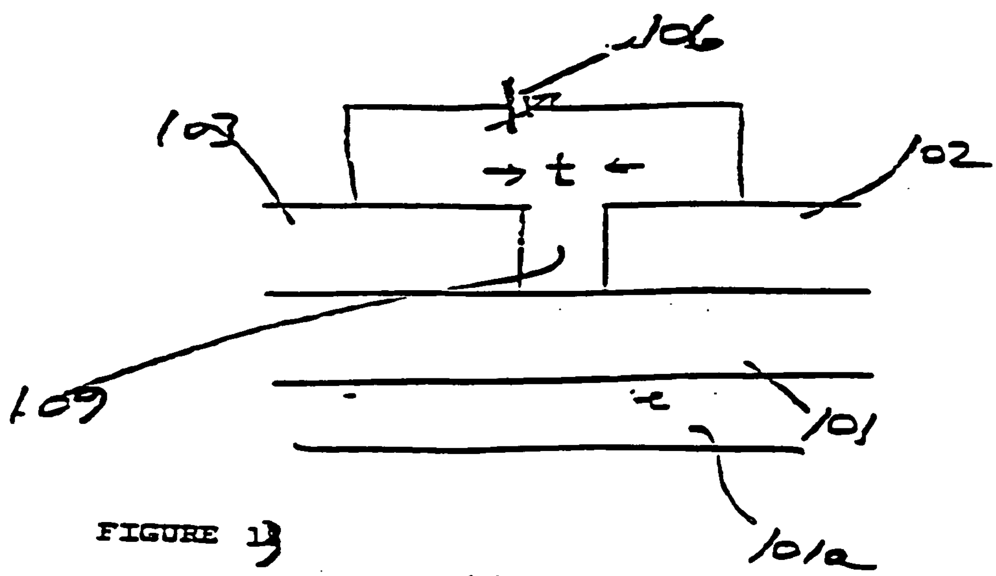


FIGURE 13

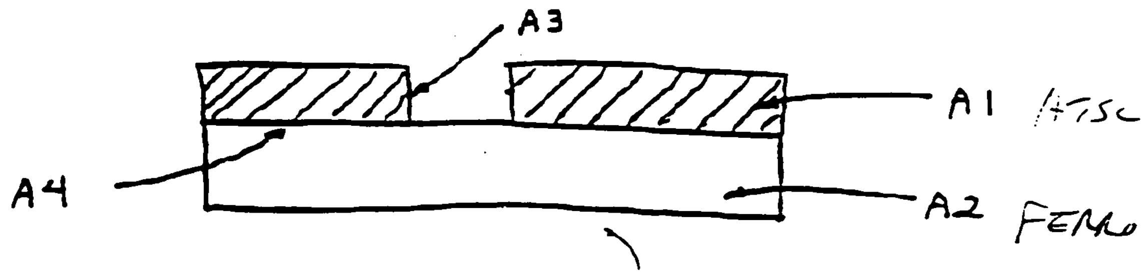


FIG. 14

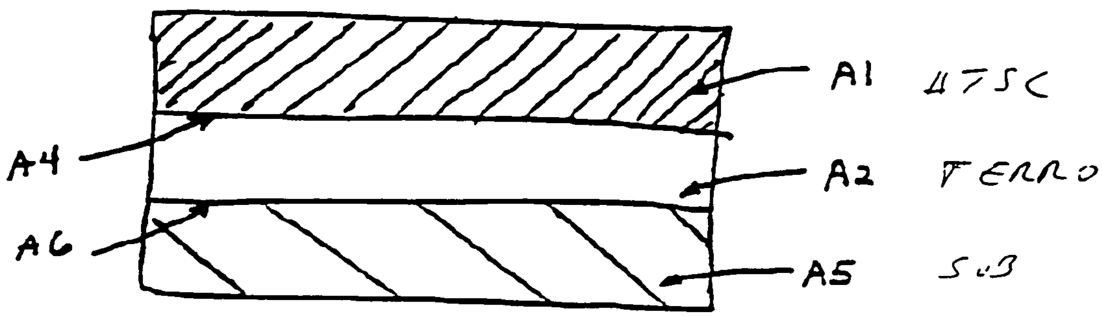


FIG. 15

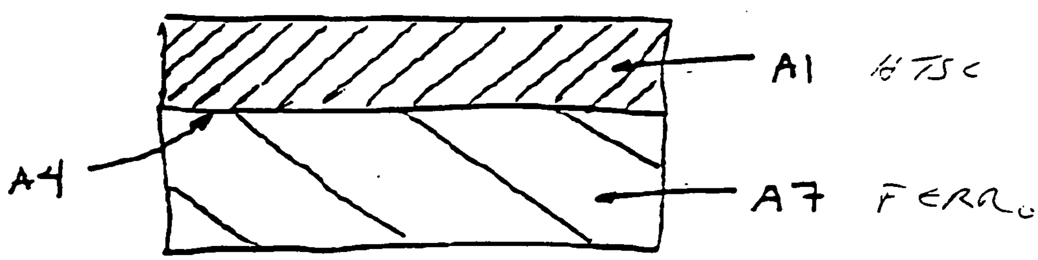


FIG. 16

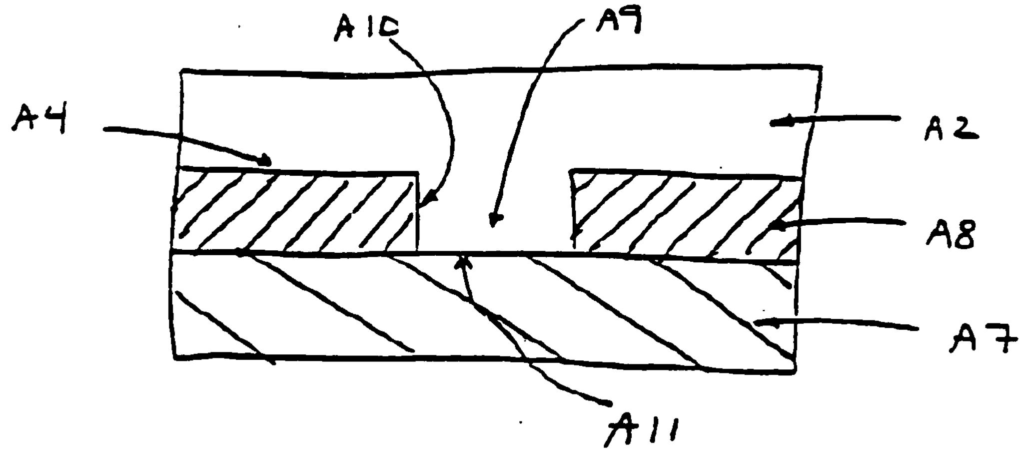


FIG.17

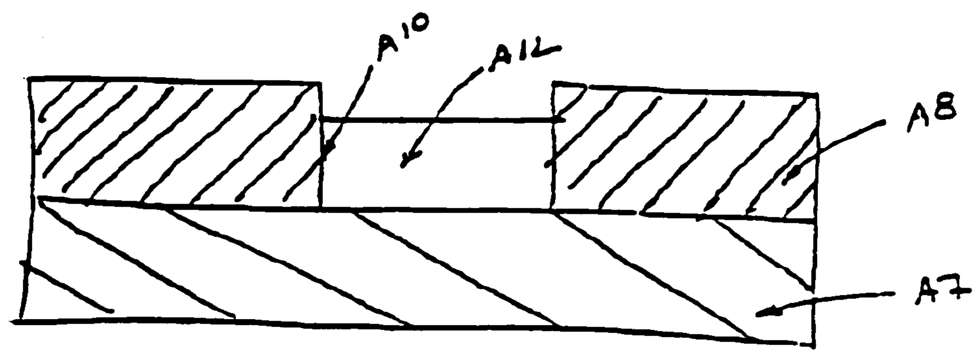


FIG.18

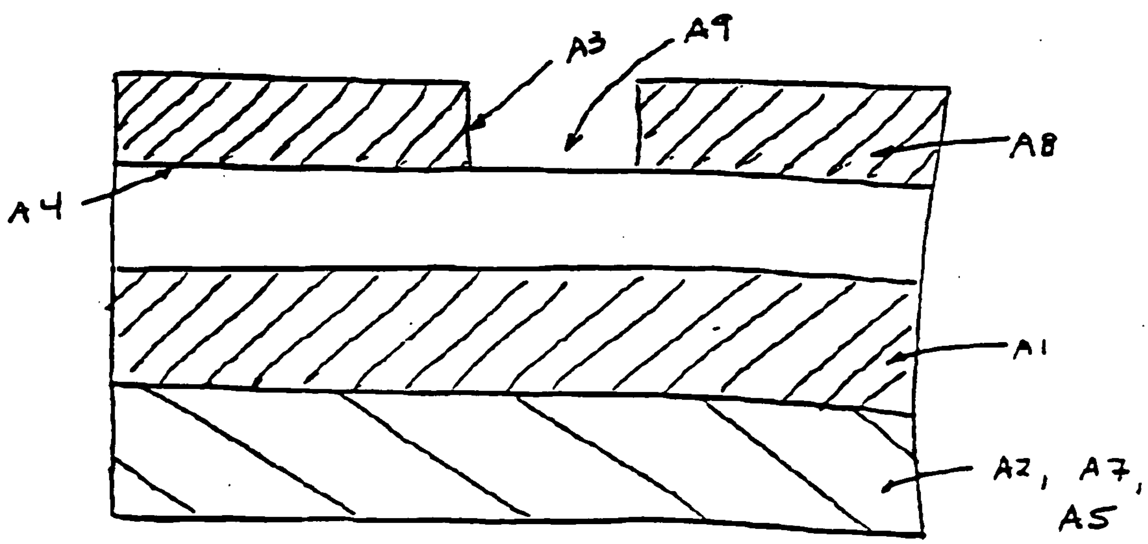


FIG.19.

FIG. 20

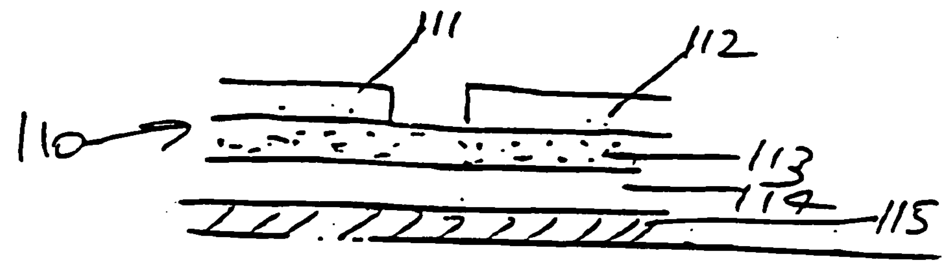


FIG. 21.

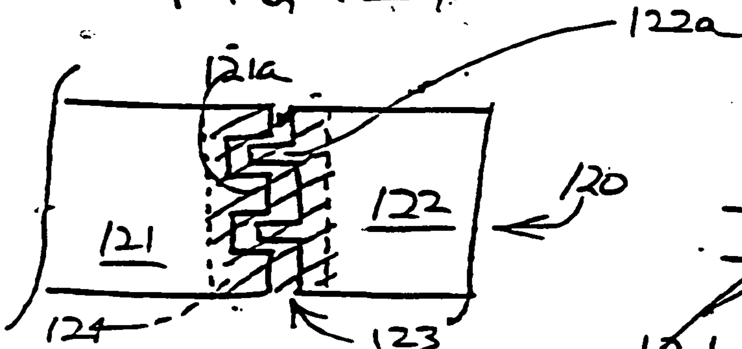


FIG. 22.

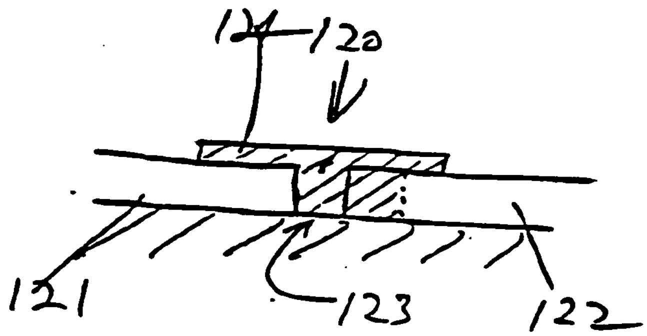


FIG. 23

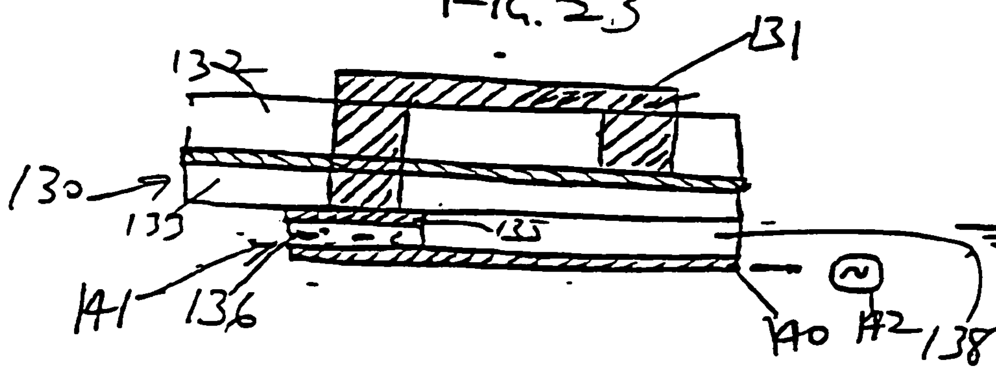
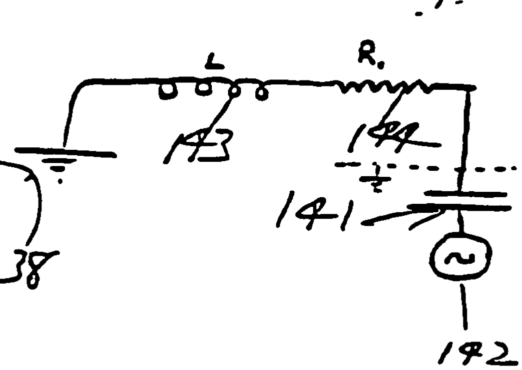


FIG. 24



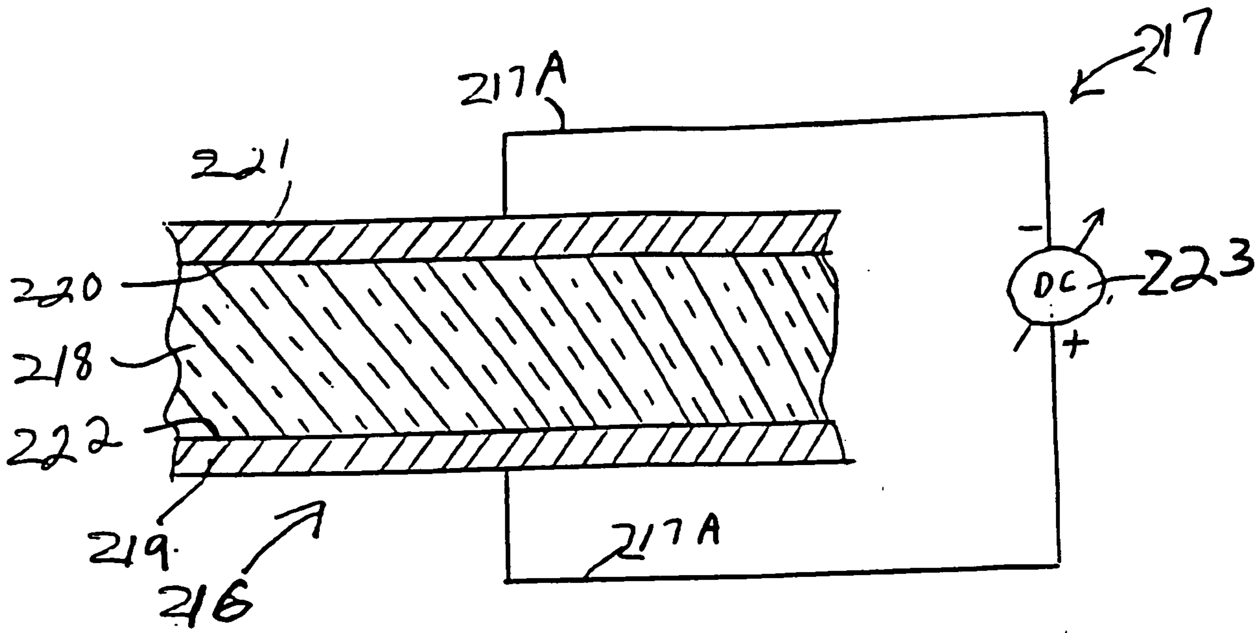

217A
217
221
220
218
222
219
216
DC
223
217A

FIG. 25

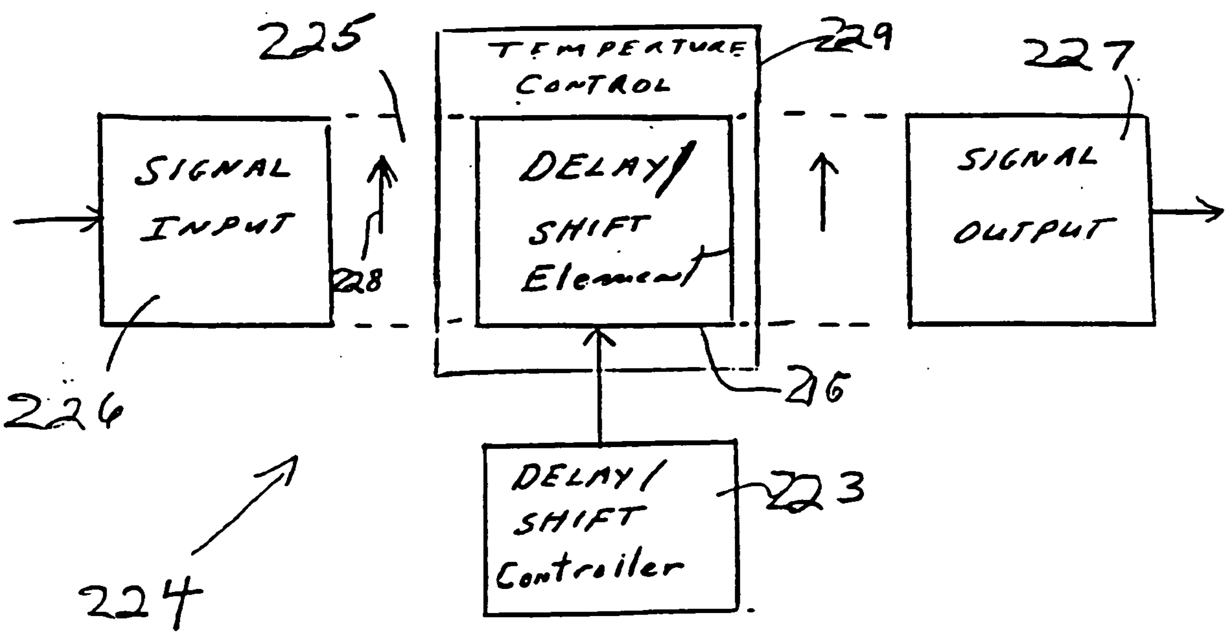

225
TEMPERATURE CONTROL
229
227
SIGNAL INPUT
DELAY/SHIFT Element
SIGNAL OUTPUT
228
226
216
DELAY/SHIFT Controller
223
224

FIG. 26

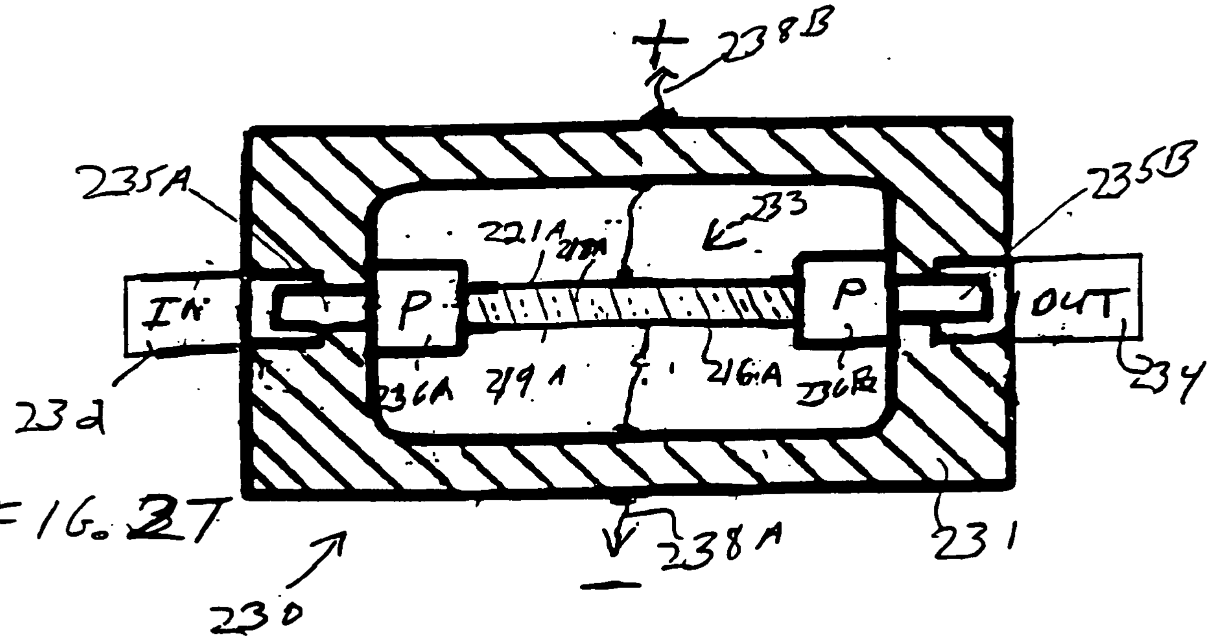


FIG. 27

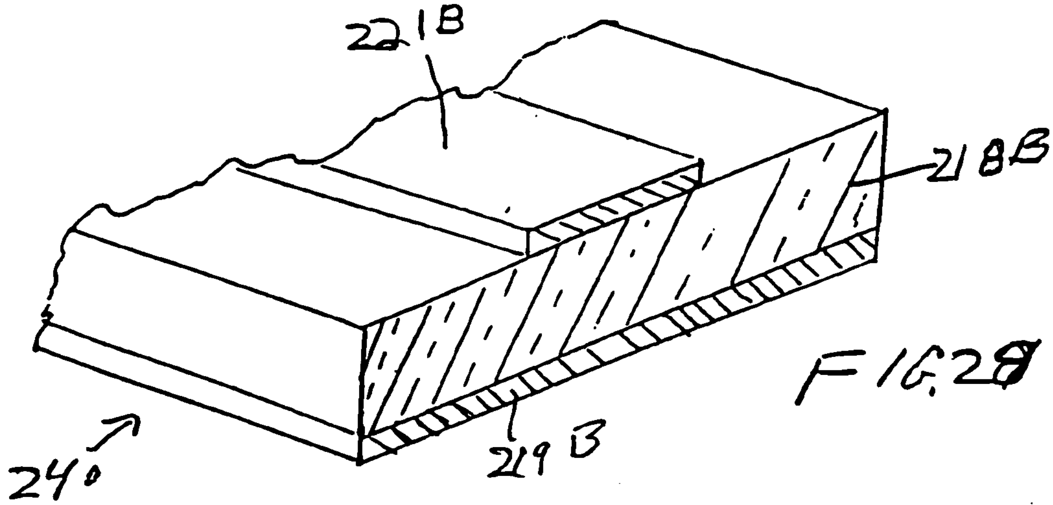


FIG. 28

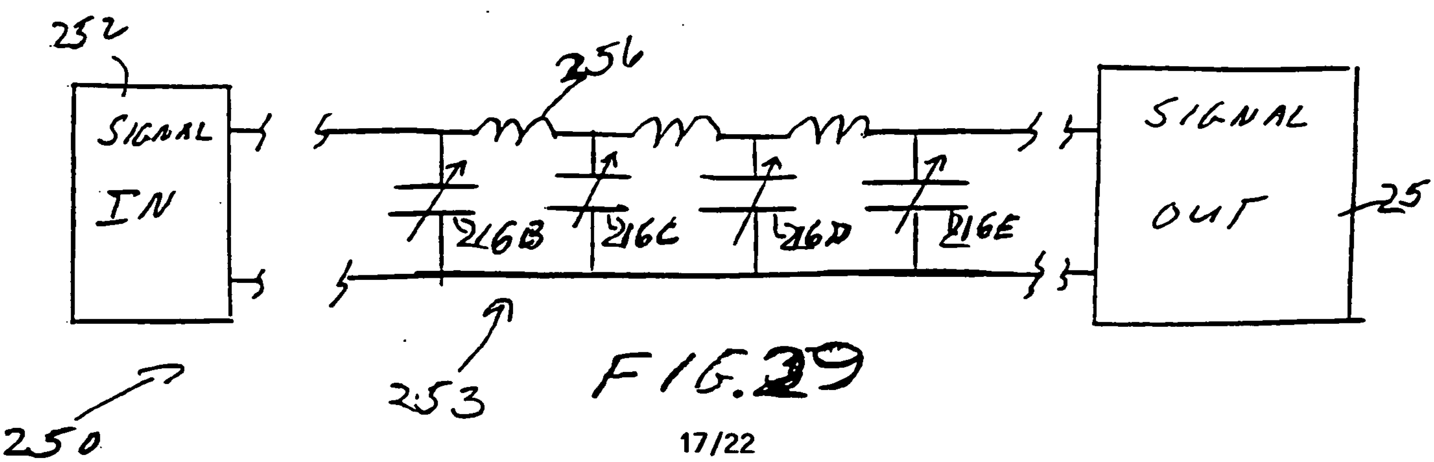


FIG. 29

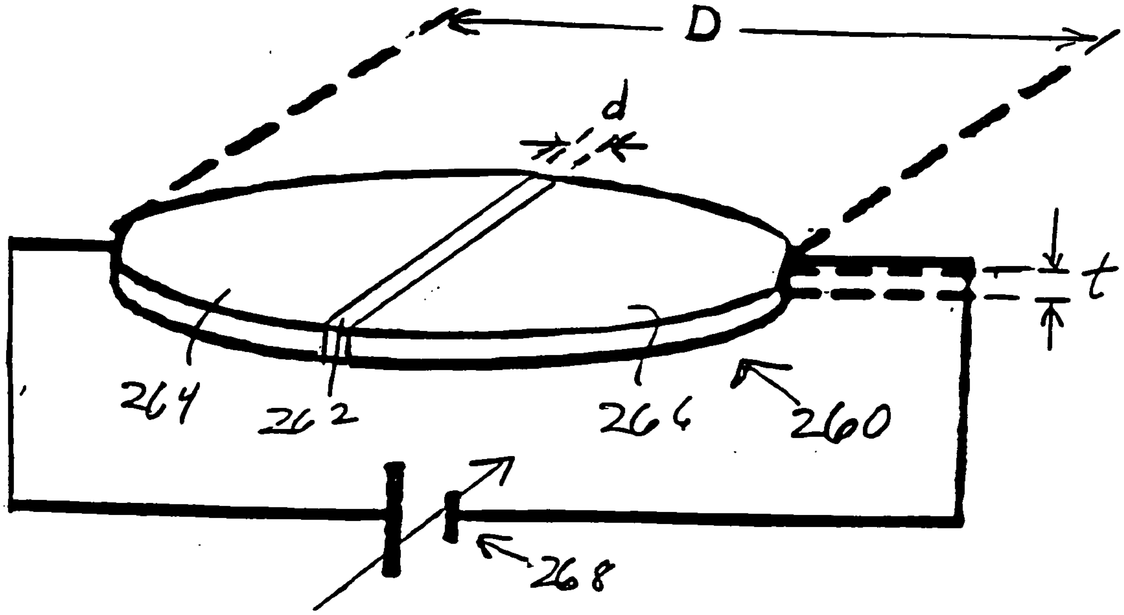


FIG. 30

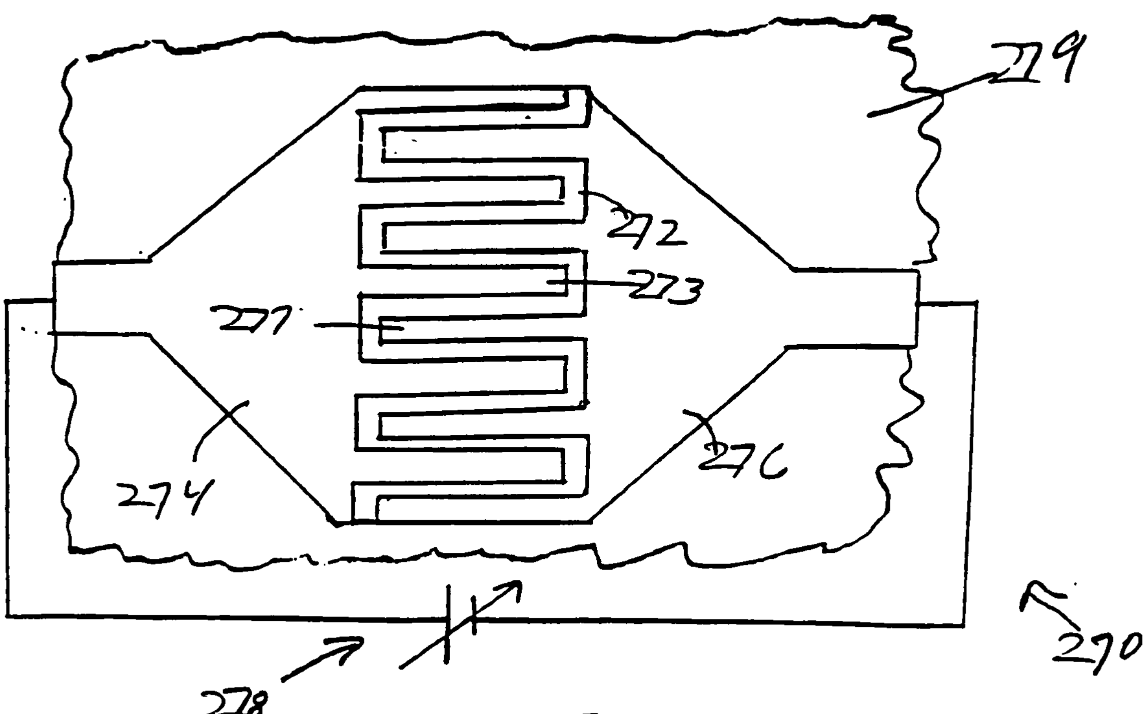


FIG. 31

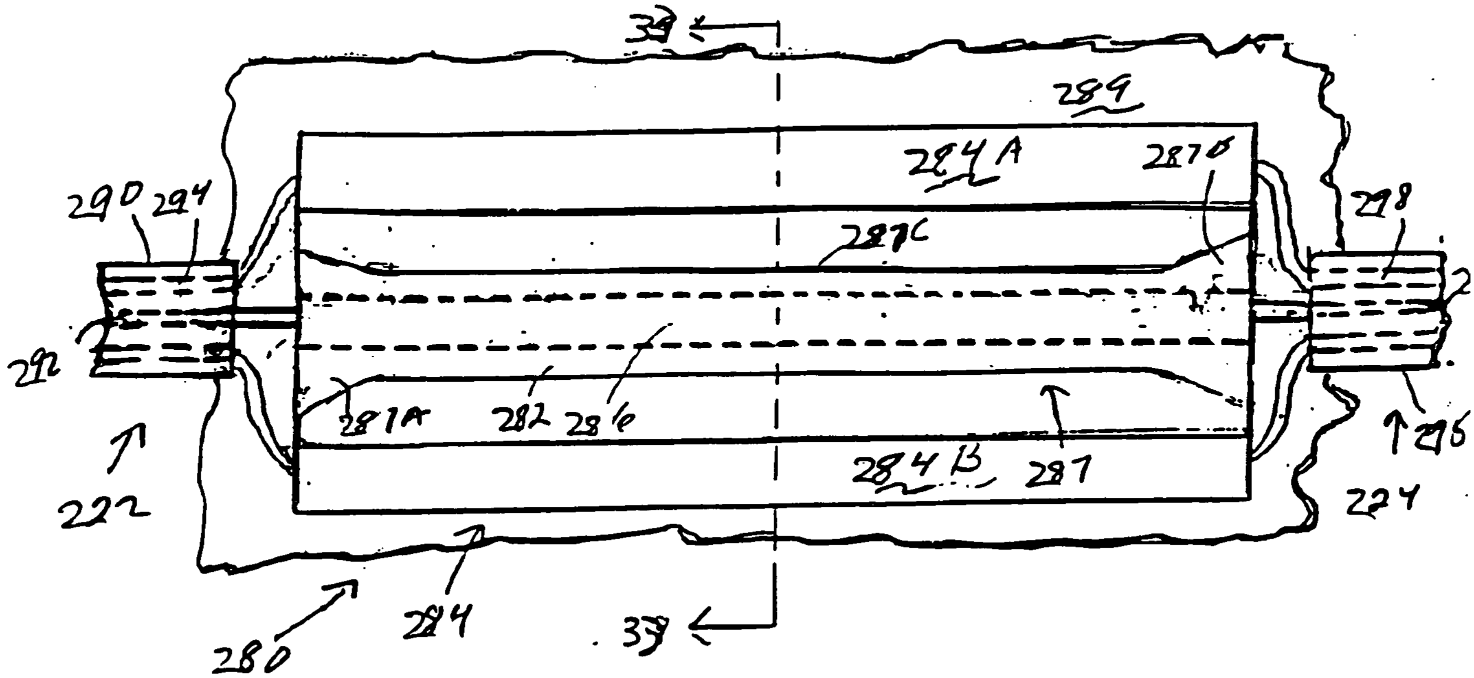

33
289
284A
287B
290 294
298
287C
292
287A 282 286
284B 287
222
224
296
280
284
33

FIG. 32

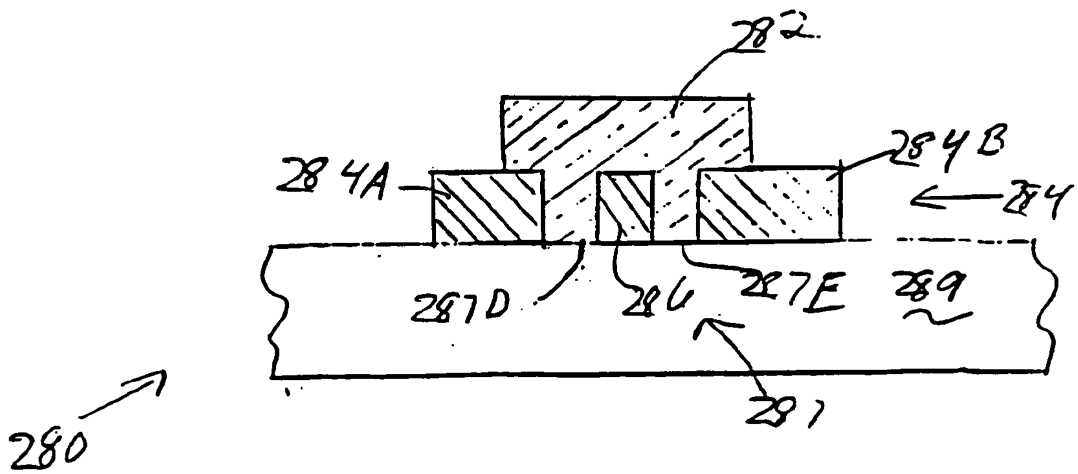
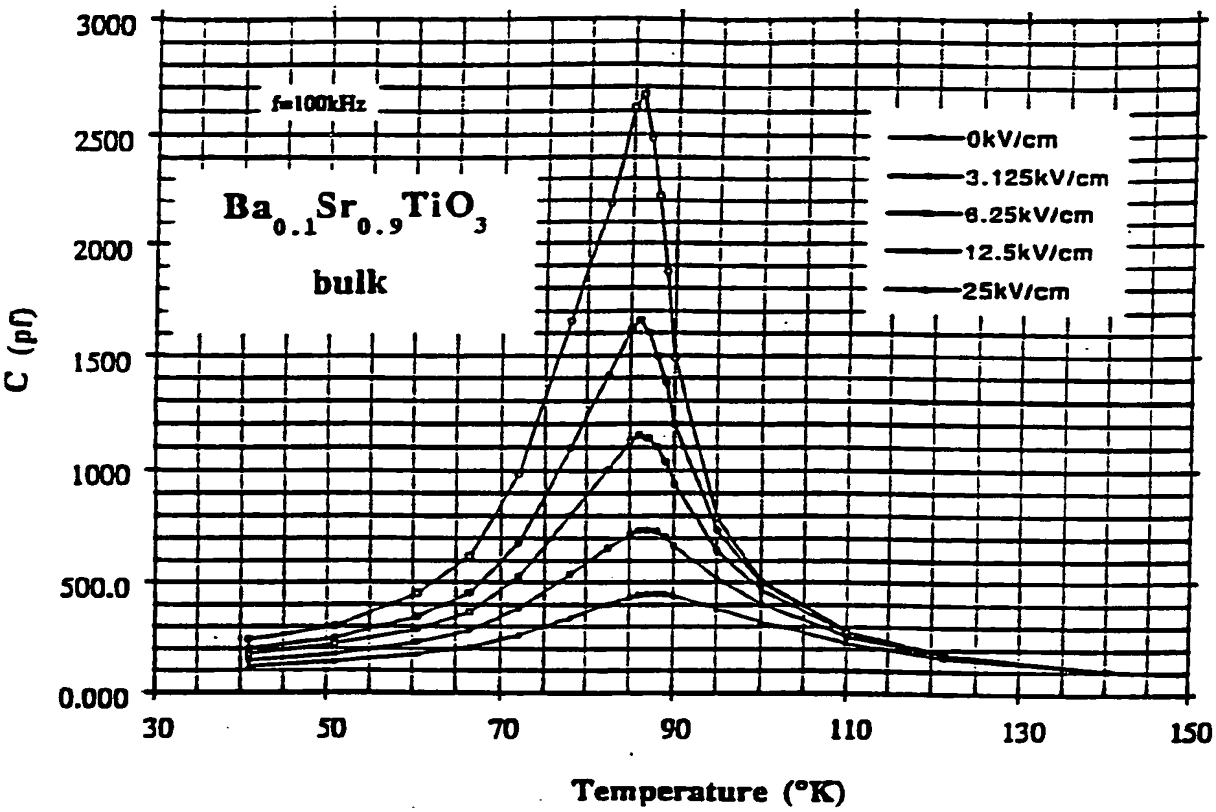

282
284B
284A
284
287D
286
287E
289
287
280

FIG 33

FIG. 34


3000
2500
2000
1500
1000
500.0
0.000
C (pf)
f=100kHz
$Ba_{0.1}Sr_{0.9}TiO_3$
bulk
0kV/cm
3.125kV/cm
6.25kV/cm
12.5kV/cm
25kV/cm
30
50
70
90
110
130
150
Temperature (°K)

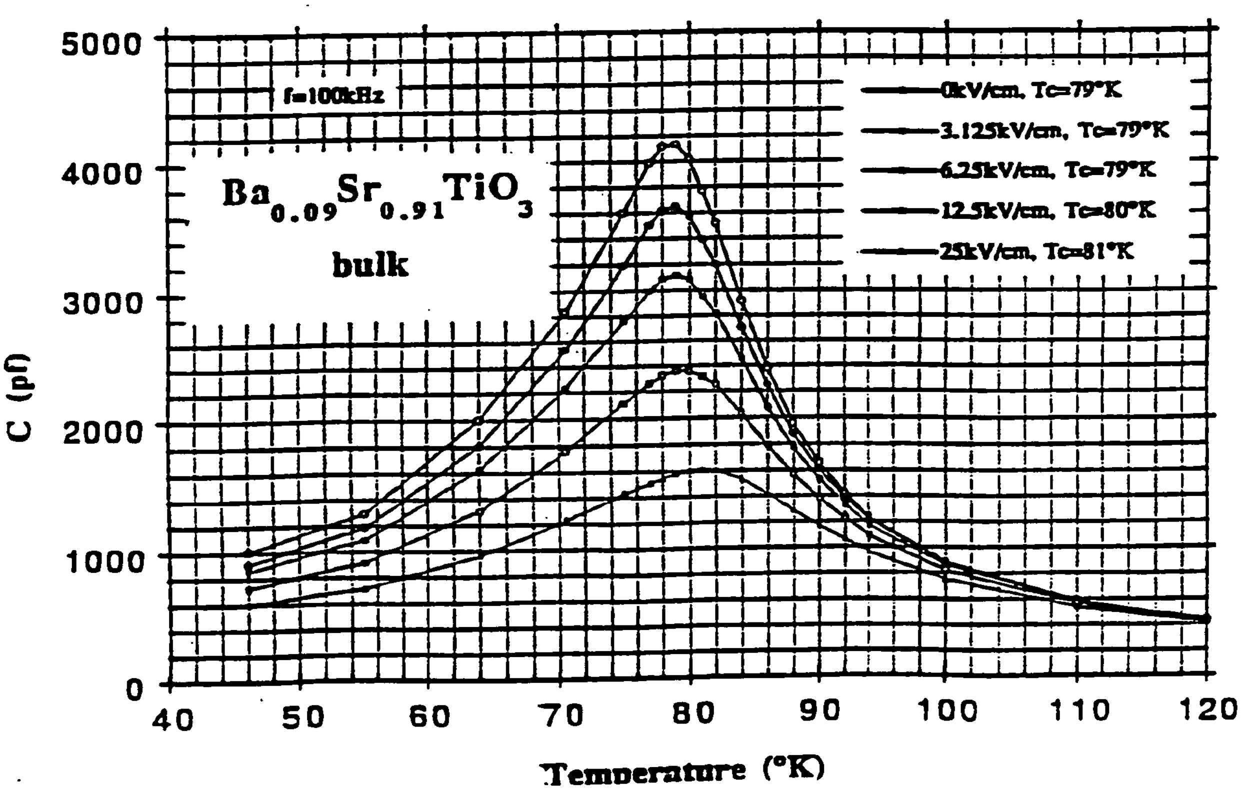
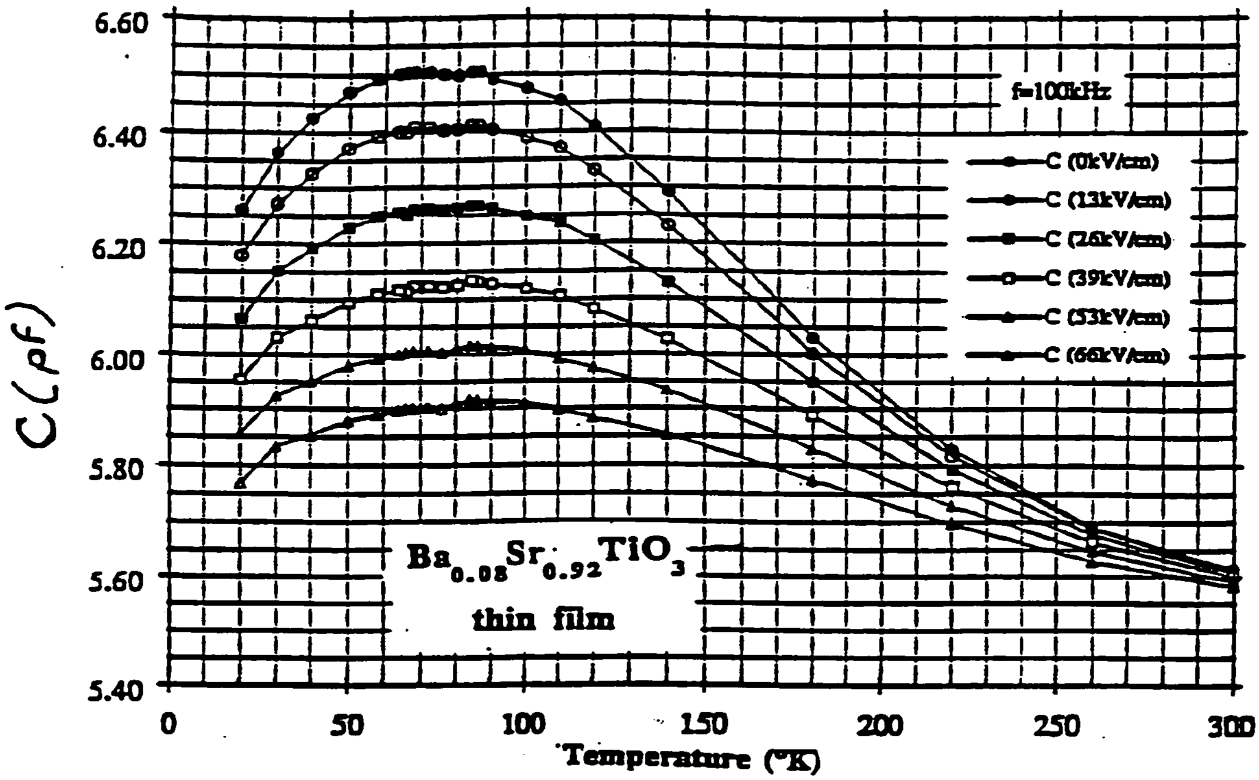
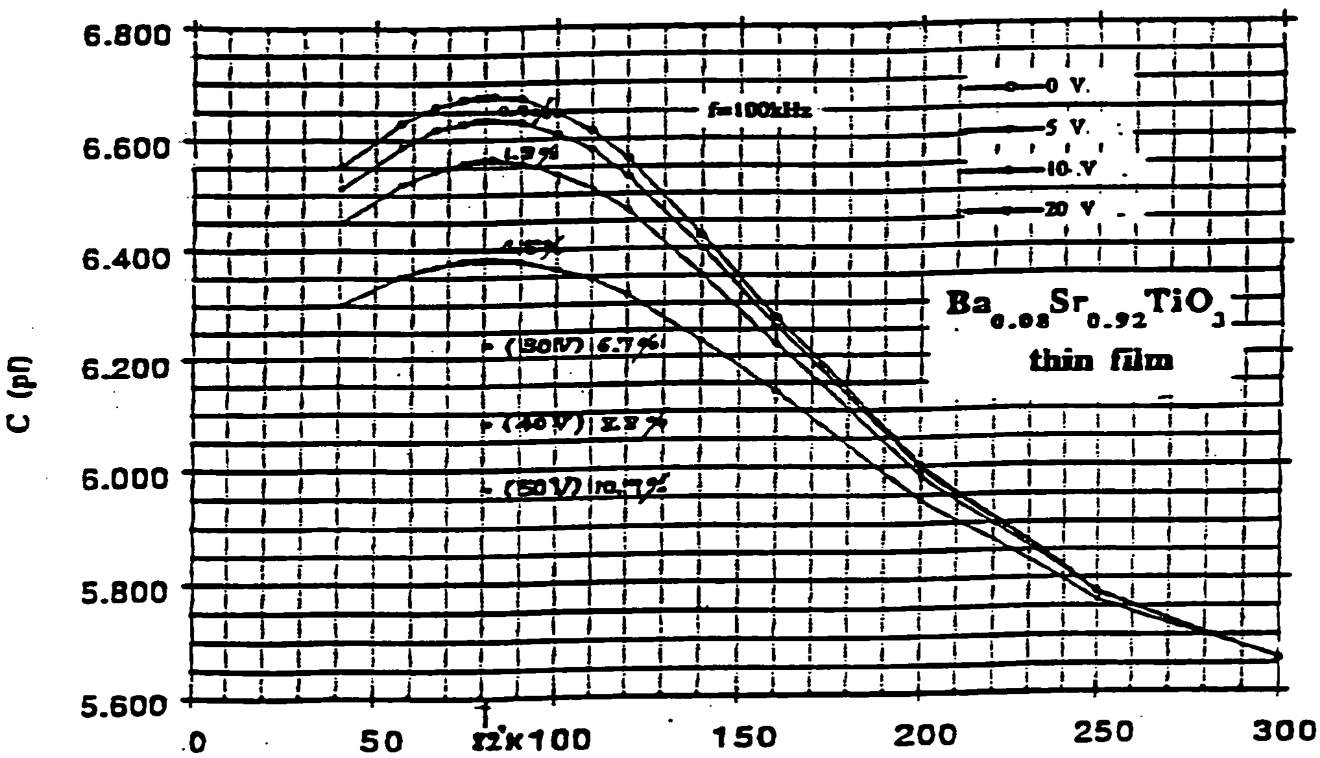

5000
4000
3000
2000
1000
0
C (pf)
f=100kHz
$Ba_{0.09}Sr_{0.91}TiO_3$
bulk
0kV/cm, Tc=79°K
3.125kV/cm, Tc=79°K
6.25kV/cm, Tc=79°K
12.5kV/cm, Tc=80°K
25kV/cm, Tc=81°K
40
50
60
70
80
90
100
110
120
Temperature (°K)

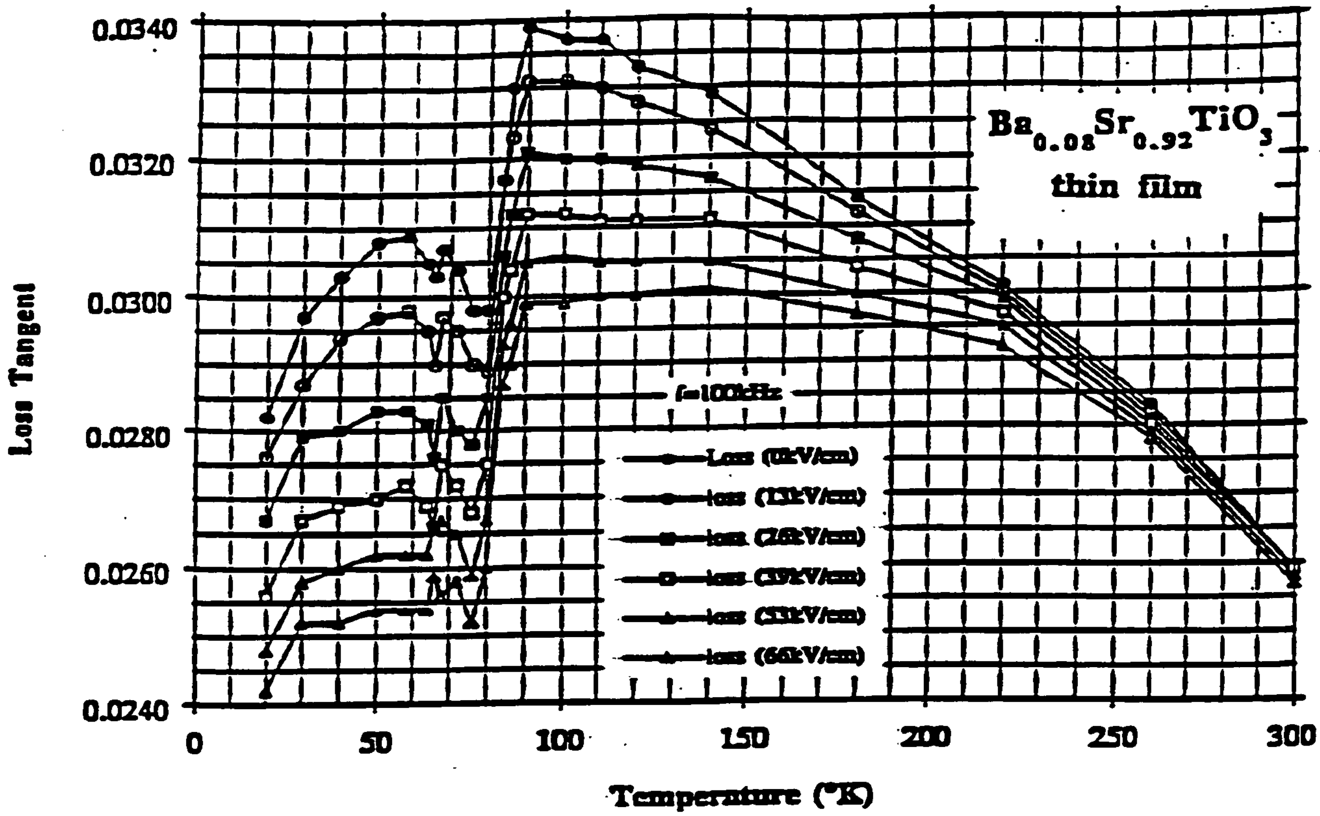
FIG 36





Temperature (°K) FIG. 37

FIG 38


0.0340
0.0320
0.0300
0.0280
0.0260
0.0240
Loss Tangent
0
50
100
150
200
250
300
Temperature (°K)
$Ba_{0.08}Sr_{0.92}TiO_3$
thin film
f=100kHz
Loss (0kV/cm)
loss (13kV/cm)
loss (26kV/cm)
loss (39kV/cm)
loss (53kV/cm)
loss (66kV/cm)

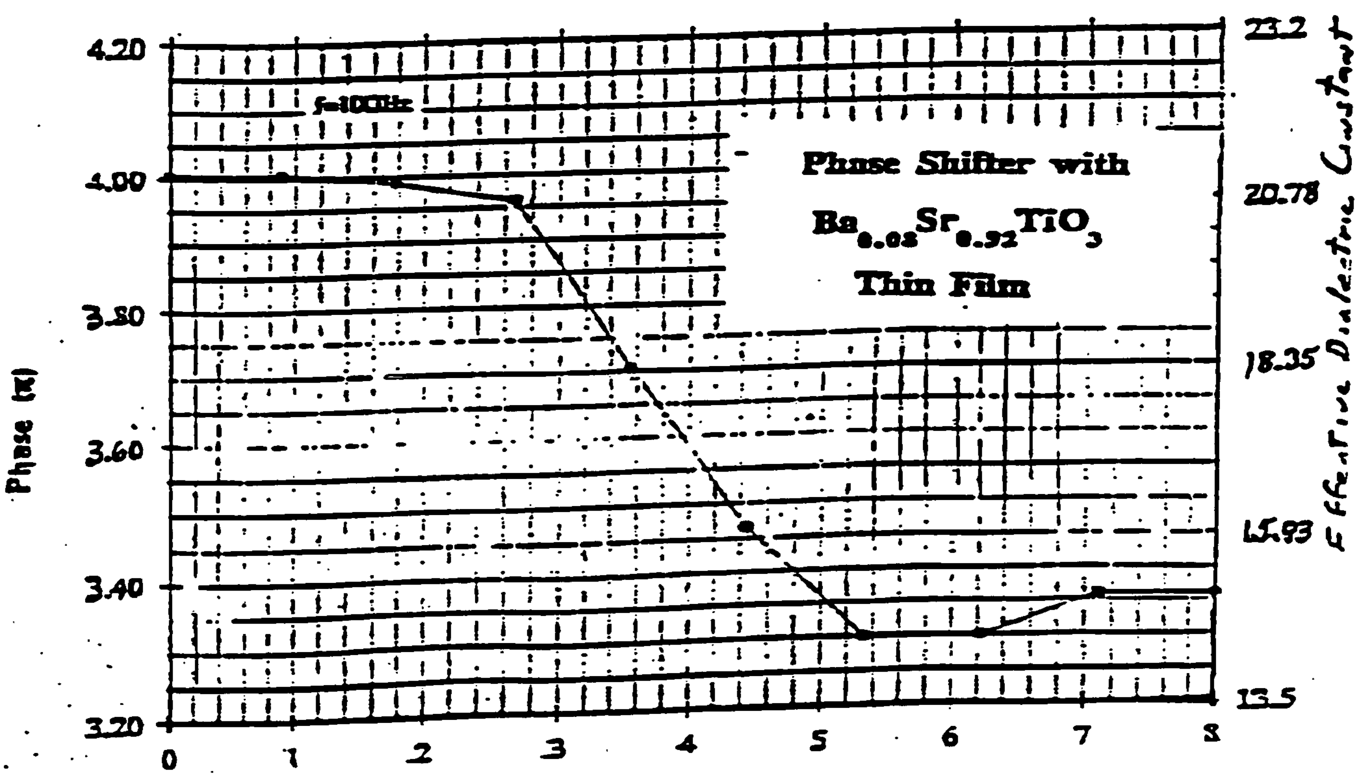

4.20
4.00
3.80
3.60
3.40
3.20
Phase (π)
23.2
20.78
18.35
15.93
13.5
Effective Dielectric Constant
f=100kHz
Phase Shifter with
$Ba_{0.08}Sr_{0.92}TiO_3$
Thin Film
0
1
2
3
4
5
6
7
8

FIG 39

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/11780

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :Please See Extra Sheet.
US CL :Please See Extra Sheet.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 505/1, 700, 701, 866; 333/161, 99S, 219, 235,238, 246; 343/700R, 700MS, 741, 744, 753, 754, 910; 342/371, 372, 373; 361/281, 280, 277, 305, 321.4, 321.5, 322; 257/295

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US, A, 5,208,213 (Ruby) 04 May 1993, see figs. 2 & 4, and col 2, lines 27-45.	1,3,5-10, 39-42
Y,P	US, A, 5,212,463 (Babbitt et al) 18 May 1993, see fig. 1 and col 3, lines 15-46	1,3,5-10, 39-42
Y	JP, A, 205,904 (Higaki) 09 September 1991, see abstract and fig. 2	1,3,5-10, 39-42

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be part of particular relevance
- "E" earlier document published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 March 1994	25 APR 1994

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. NOT APPLICABLE	BENNY LEE Telephone No. (703) 308 4902

INTERNATIONAL SEARCH REPORT

In ational application No.
PCT/US93/11780

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest
☒ The additional search fees were accompanied by the applicant's protest.
☐ No protest accompanied the payment of additional search fees.

A. CLASSIFICATION OF SUBJECT MATTER:
IPC (5):

H01P 1/18, H01P 3/08, H01P 7/08: H01B 12/02; H01L 39/06; H01Q 3/00, H01Q 7/00, H01Q 9/00, H01Q 15/00; H01G 7/06

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

505/1, 700, 701, 866; 333/161, 99S, 219, 235, 238, 246; 343/700MS, 744, 910; 342/371; 361/281

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

I. Claims 1-10,39-42, drawn to a tuneable superconducting electronic component/phase shifter classified in Cl 333/161;
II. Claims 11-19, drawn to a tuneable superconducting electric antenna/array classified in Cl 343/700MS;
III. Claims 20-22, drawn to a superconducting phase array antenna classified in Cl 342/371;
IV. Claims 23-26,32-35, drawn to a tuneable superconducting fringe effect capacitor classified in Cl 361/281;
V. Claims 27,28 drawn to a tuneable superconducting coplanar electrical component classified in Cl 333/246;
VI. Claims 29-31, drawn to a capacitively coupled superconducting microstrip resonator classified in Cl 333/219;
VII. Claims 36-38, drawn to a tuneable superconducting loop antenna classified in Cl 343/741;
VIII. Claims 43-52,58-64,70-75,81-84, drawn to a tuneable ferroelectric (i.e. BST) electrical device classified in Cl 333/99S;
IV. Claims 53,65,76, drawn to a tuneable ferroelectric coplanar waveguide phase shifter classified in Cl 333/161;
X. Claims 54,66,77, drawn to a tuneable ferroelectric fringe effect capacitor classified in Cl 361/281;
XI. Claims 55-57,67-69,78-80, drawn to a tuneable ferroelectric transmission line classified in Cl 333/238;